United States Air Force
Scientific Advisory Board

Report on

A Space Roadmap for the 21st Century Aerospace Force

Volume 3: Appendices F - J

SAB-TR-98-01

December 2000

Cleared for Open Publication

This report is a product of the United States Air Force Scientific Advisory Board Committee on *A Space Roadmap for the 21st Century Aerospace Force*. Statements, opinions, recommendations, and/or conclusions contained in this report are those of the Committee and do not necessarily represent the official position of the USAF or the Department of Defense.

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ABSTRACT (Maximum 200 Words)

The Air Force Scientific Advisory Board produced this study. The Chief of Staff of the Air Force and Secretary of the Air Force requested the study. It presents the Committee-recommended steps the Air Force should take to make the best use of space in accomplishing its assigned operational tasks in a rapidly changing world. While this report stands alone, it builds on the foundation of the Doable Space Quick-Look study led by the Air Force Chief Scientist and it complements the Aerospace Integration Task Force work.

14. SUBJECT TERMS

Global Engagement, *Joint Vision 2010* (*JV2010*), Aerospace Force, 21st Century, Aerospace Integration Task Force (AITF), Global Grid, Information Architecture, Space-Based Radar (SBR), Position, Navigation, and Timing (PNT), Global Energy Projection, Recognized Space Picture (RSP), Common Operating Picture (COP), Space Assets, Modeling, Simulation and Analysis (MS&A), Aerospace Operations Vehicle (AOV), National Launch Facilities, Commercial Models, Commercial Acquisition

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Foreword

". . . and it ought to be remembered that there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things . . ." Niccolo Machiavelli

"Just DO it!"   Nike slogan

The United States Air Force faces enormous challenges in evolving to an integrated aerospace force that has the capabilities needed to cope with the military challenges of the next century. Between today's air and space forces and the desired end state that is emerging from long-range planning lies a difficult and uncertain path. The Air Force Scientific Advisory Board was asked to help the Air Force map that path, and we have tried to lay the foundation of a roadmap for achieving the envisioned future of aerospace power. While this report stands alone, it builds on the foundation of the Doable Space Quick-Look study led by the Air Force Chief Scientist, and it complements the work of the Aerospace Integration Task Force, which has been chartered to develop an Aerospace Integration Plan.

All of us who worked on this study are grateful for the opportunity to participate in this important effort, and we hope our recommendations will help the Air Force make sound decisions and deal effectively with the contentious issues involved.

Dr. John M. Borky
Study Chairman

November 1998

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Abstracts for Appendices F–J

This report consists of three Volumes. Volume 1 is the Summary Volume of the report. Volume 2 is Appendix E, Operational Requirements and Force Integration, and Volume 3 contains Appendices F-J:

Appendix F: Architecture and Information Management

Appendix G: Payloads

Appendix H: Vehicles and Lift

Appendix I: Terrestrial Segment

Appendix J: Cost Estimation and Acquisition Strategy

A short summary of the contents of each appendix follows.

Architecture and Information Management: Volume 3, Appendix F

The Architecture and Information Management Panel's portion of the Scientific Advisory Board Summer Study evaluated the status, ongoing dynamic changes, and exciting future of the Air Force Information Management Architecture. This appendix will report on the critical aspects leading to aerospace power through information dominance. Global Knowledge, Global Reach, and Global Power are all critically dependent on robust network-centric Global Grid information management architecture. This panel concentrated on two tasks. The first was to establish a baseline architecture to determine the validity of options within the aerospace roadmap. The second was to evaluate the state of Air Force information management activities.

The complexity and extent of the architectures involved in the current and future national security environment dictate the adoption of a consistent framework for the entire study. That framework accepts the premise that, for the foreseeable future, systems cannot be considered in isolation from each other or in isolation from the architecture they comprise. Beyond that, architectures can no longer be considered in isolation from other architectures with which they interface. The architectural framework used in the Summer Study included (a) an "Operational Architecture" that identifies essential nodes in some operationally relevant context with the interconnectivity between each node and (b) a "Systems Architecture" that provides the technical systems with a response to the operational need in terms of physical characteristics and performance parameters. Across the Air Force's aerospace framework, there are multiple systems architectures, each composed of several systems. The evaluation of the Air Force Information Management Architecture led to some major recommendations and findings.

The Air Force needs an information management architecture to realize the full potential of aerospace power capabilities. Information management touches upon a host of important military needs from intelligence, surveillance, and reconnaissance to command and control (C^2) of forces. Each commander will be able to tailor the architecture envisioned in this report to the specific mission for which he or she is responsible. The architecture will integrate information from global and theater assets, both inside and outside the Air Force, and enable seamless C^2 of forces around the globe. In addition, it will exploit commercial technologies in order to be technologically current and affordable. The future information architecture will include elements based in space, in the air, and on the surface of the globe. Many of these systems may be operated by the military Services of the United States, allies, or coalition partners. However, the majority of the systems will be operated by commercial companies, both domestic and international. The information management architecture recommended in this report is intended to modernize Air Force military capabilities and to be a key enabler of new operational concepts for the employment of aerospace power.

Commanders rely on information to depict the battlespace, detect attack, determine adversary intent, define capabilities, and direct the maneuver and positioning of commanded forces. C^2 depends on the exploitation of information. This critical reliance underwrites the *JV2010* tenet of Strategic Dominance and is the basis for the Air Force's Global Engagement goal of Information Dominance. Achieving Information Dominance requires universal connectivity among deployed forces, CINCs, the National Command Authority, and supporting elements. This demands that the Global Grid system-of-systems provide bandwidth and other communications functions to support the expeditionary Aerospace Force (eAF) mission and Information Dominance. Lean and mean eAF operations will demand that C^2 be distributed and collaborative. Virtual battlestaffs will be the central elements in future C^2. Improved connectivity—through the Global Grid—is the fundamental enabler for the eAF operational concept.

Overview of Architecture and Information Management

Section Number	***Title***
1.0	Introduction
2.0	Aerospace Force Structure and Architectural Approach
3.0	Information Management Philosophy
4.0	Information Management Structure
5.0	Vision for Air Force Information Management
6.0	Technology Enablers
7.0	Migration Strategy
8.0	Acquisition Strategy

Payloads: Volume 3, Appendix G

The Payloads Panel examined topics of significance to defense missions that either currently have a space segment or might, in the view of the panel, justify a space segment in the future.

Historically, DoD missions have taken advantage of the high ground of space to collect—with passive receivers—electromagnetic energy that passes easily through the earth's atmosphere (visible, infrared, and radio frequency) for electronic intelligence, communications intelligence, imagery intelligence, measurement and signals intelligence, weather forecasting, and warning. The receivers relay radio-frequency communications with relatively low-power spacecraft (10^2 to 10^3 watts) to provide precision passive terrestrial navigation through one-way range measurement based on precision timing distributed from space.

While commercial forces have increased spacecraft total power to approximately 10^4 watts and, through increased demand for commercial launch services, stimulated a significant drive toward lower-cost launches, there is no foreseeable scenario in which payload weight and power consumption are not major constraints on space system design.

In structuring this study of payloads for the future, existing missions with space segments were parsed into their basic elements to allow the generic underlying science, technology, engineering, and art to be dealt with as they might be applied across multiple missions and applications. Thus the current space missions, including communications, intelligence, weather, surveillance/warning, and navigation, are mapped into technology areas. This study is not comprehensive in the sense that not all current space missions were examined in depth to suggest appropriate payloads for future missions. The sections individually focus on major payload investment areas of the near term, system architecture and integration issues, and technologies of interest for the future.

Overview of Payloads

Section Number	***Title***
1.0	Introduction
2.0	Space-Based Radar
3.0	Communications
4.0	Navigation, Position, and Timing
5.0	Space-Based Electro-Optical (Visible/Infrared) Systems
6.0	System Architecture and Integration Issues
7.0	Roles for Small Satellites
8.0	RADSAR
9.0	Space Power Technologies
Annex	SATCOM Frequencies Usage

Vehicles and Lift: Volume 3, Appendix H

The Vehicles and Lift appendix addresses current issues and provides recommendations dealing with space launch vehicles, launch infrastructure, space operations vehicles, spacecraft buses, and potential high-leverage technology areas.

Lift vehicles are analyzed from the standpoint of metrics such as cost per unit weight to orbit, turnaround time, robustness, responsiveness, and desired level of commercial involvement. Both reusable and expendable launch vehicles are considered, with emphasis on the lift needs of Air Force systems and their differences from current and projected commercial lift requirements. The launch infrastructure portion, dealing primarily with launch pads and ranges, focuses on the increasing need to modernize the facilities and the organizational structure to support the projected growth in commercial launches. The Aerospace Operations Vehicle is presented based on a military concept of operations. Spacecraft buses are addressed in terms of the adaptation of commercially available buses for unique military requirements to minimize cost and cycle time. Radiation susceptibility of commercial low earth orbit and geostationary earth orbit buses is described. The chapter concludes by describing high-leverage technologies that can revolutionize the approach to spacecraft and launch vehicle structures and propulsion, and satellite power generation.

Overview of Vehicles and Lift

Section Number	***Title***
1.0	Introduction
2.0	Summary Findings and Recommendations
3.0	Expendable Launch Vehicles
4.0	Launch Infrastructure
5.0	Reusable Space Launch Vehicles
6.0	Aerospace Operations Vehicle System
7.0	Spacecraft Buses
8.0	High-Leverage Technologies for Air Force Investment

Terrestrial Segment: Volume 3, Appendix I

The Terrestrial Segment Panel was tasked to consider options for reducing the cost of acquiring and operating military ground systems, recognizing that roughly half the life-cycle cost of military space systems is entailed in this area. The growth of the commercial space industry has yielded products, services, and operational practices that are substantially more cost-effective than current Air Force operations, notably in the area of satellite operations. A comparison sometimes cited is that the Air Force has about 2,000 people operating about 100 satellites, whereas the Iridium constellation has about 200 people operating 60 satellites. Since the Air Force is now in a position to consume and use technology, rather than create it, the Air Force must learn to *use commercial first* in order to leverage these cost benefits.

The panel also considered the issues associated with seamless integration of space systems into overall command and control and combat operations. Military operational effectiveness can be greatly improved by taking a mission-centric (or capability-centric) view across a system-of-systems architecture including air, space, and terrestrial components. This evolutionary migration from a platform-centric view can enable new capabilities and expanded services while maintaining backward compatibility with existing infrastructure and user equipment. Implementation of this vision will require the development of robust connectivity across the battlespace, tying together planning, sensing, processing, and user elements (or nodes) of the air, space, and ground segments of a battlespace network.

To leverage the rapid advances in commercial technology for satellite operations, the Air Force must adopt new acquisition practices. The traditional DoD acquisition process takes a minimum of 5 years for development, while commercial information technology performance improves 100 times every 10 years. The Air Force should make both a revolutionary change—switching from military to civilian models for system development, procurement, and operations—and an evolutionary change based on continuous improvement throughout the program, using the spiral development process as a model.

Human factors remains a perennially neglected discipline, with serious long-term consequences. Poorly designed operator stations and other aspects of the human-system interface affect everything from the effectiveness of system operation to training requirements to morale. The root problem is that neither the Government nor contractors treat human factors as a critical aspect of system requirements and a mandatory element of the system engineering process. As long as the problem is ignored, a host of unnecessary costs, many of them hidden, will continue to be paid. To resolve this problem, we recommend that the Air Force incorporate human factors as an integral part of the acquisition process.

Overview of Terrestrial Segment

Section Number	***Title***
1.0	Introduction
2.0	Commercial Practices for Satellite Operations
3.0	Mission-Centric Distributed Architecture
4.0	Connectivity for the Network-Centric Battlespace
5.0	Spiral Development: Moving to Best Commercial Practices
6.0	Human Factors
7.0	Conclusions and Recommendations

Cost Estimation and Acquisition Strategy: Volume 3, Appendix J

The Cost Estimation and Acquisition Strategy report is a forecast of a potential future for the Air Force, but does not necessarily imply future officially sanctioned programs, planning, costs, or policy.

In the 52-year history of the Air Force Scientific Advisory Board, we have made estimates of the future and technology. We understand the uncertainties that accompany any attempt to predict the future; most predictions become increasingly inaccurate after a decade or so. In that respect this study is no different than the others that have preceded it; however, this is the first SAB study to add the dimension and complication of cost estimation.

Today, we assert that affordability must be emphasized as much as technology, for it is the hard-earned dollars of the American taxpayer that pay for our national security. In the Cold War, a monolithic threat and potential scenarios were well known. But in the current and expected environment of constrained budgets, we must train and equip our military forces for a diverse set of situations across the full spectrum of conflict. These constraints require that the cost and performance of competing potential systems be evaluated and compared.

With an environment of limited dollars and competing solutions to ill-defined problems, we must evaluate the rising capabilities of commercial technologies and enterprises as we consider divestiture of support functions. This brings another dimension to the cost-effectiveness of any force options analysis and requires new approaches to meeting Air Force goals.

Lord Rutherford once said, *"We are out of money and thus, we must think."* This study represents that thought process. Other panels addressed the capabilities enabled by the new technologies we envision. Here we delineate the cost methodology and the relative costs of those envisioned force options considered. We also consider alternative means of acquiring necessary capabilities.

Overview of Cost Estimation and Acquisition Strategy

Section Number	***Title***
1.0	Executive Summary
2.0	Cost Estimation Methodology
3.0	Cost Data
4.0	Cost Panel Recommendations
5.0	Acquisition Findings
6.0	Acquisition Recommendations
Annex	Tecolote Cost-Estimating Support

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Appendix F

Architecture and Information Management (AIM)

1.0 Introduction

The Air Force of the 21st century will be significantly different from "your grandfather's Air Force." The changes in threats and vulnerability, the world situation, and the technological explosion in information management will drive changes to methods, strategy, technology, and tactics. Therefore:

> *The Air Force must rapidly evolve its information management systems and people into an enabling capability for aerospace power supporting the expeditionary Air Force.*

The world situation will include continued regional crises caused primarily by the widening gap between the "haves" and the "have-nots," both individuals and nations. The United States will remain involved in international situations, perhaps with diminished regard to location of forces. The demands on the U.S. military—imposed by the United Nations, U.S. unilateral action, and other situations—are increasing, more diverse, more dispersed, and lasting longer. Current operations tempo is exceedingly high.

Table F-1. *Global Environment*

General Factors From the Global Environment
• National objectives will be asymmetrical
• Limited living space, food, and other natural resources may cause crises, perhaps conflicts with neighboring countries
• Adversaries are expected to intimidate regional neighbors with chemical/biological weapons threats
• Military and commercial information systems (collectors, storage, processing, and communications) will be prime initial targets
• Terrorism will be a preferred weapon of the weak against the strong
• Crises will generate growing demands for U.S. humanitarian assistance
• The era of information plenty has arrived for all nations as well as for individuals

The threats and vulnerability in the next century will almost certainly be asymmetric and cover the spectrum. Information warfare will take on new significance during the early part of the next century. This dynamic and potentially catastrophic threat will increase in importance as the Air Force increases its dependency on information supremacy. Both the solution and threat will result from the phenomenal technological explosion in commercial information technology.

These external forces are entrenching the Air Force's dependency on information technology and the space environment. Effective and timely applications of the Air Force's inherent attributes of range, speed, flexibility, and long-range precision weaponry against a global array of potential adversaries, which have both modern weapons and information capabilities, will depend on the utilization of its information management resources. We can summarize unique aerospace attributes as follows:

- Air and space forces encircle the globe seamlessly and meet less resistance to movement than forces in other mediums
- Aircraft and spacecraft can be moved very rapidly anywhere in the world

- Air and space offer unique vantage points from which to observe worldwide activities and, if necessary, engage targets
- Advanced technologies enable the employment of air-delivered weapons with greater lethality and precision

1.1 Information Management Architecture Vision

The vision for an information management architecture should be

- Mission-centric rather than platform-centric
- Developed from capable components
- "Custom tailored" by each commander
- Adaptable to new situations
- The enabler for the commander's command and control (C^2) concept
- Based on a seamless Global Grid
- Capable of exploiting U.S. technological strengths
- Crossing all "stovepipes"
- The network-centric backbone
- Based on information rather than systems

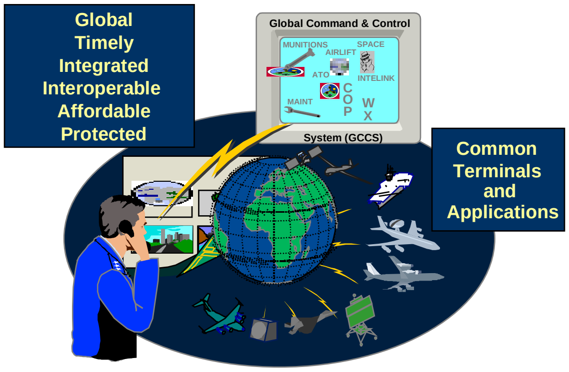
The Air Force needs to establish, and, in cooperation with the Assistant Secretary of Defense/Command, Control, Communications, and Intelligence, disseminate throughout the Department of Defense (DoD) a common information management architecture. This development, codification, and articulation of a common information architecture would provide the rapid incorporation of information warfare tactics, strategies, and training.

1.2 Major Conclusions and Recommendations

During the many stops on the 1998 Summer Study tour, we identified a few important findings. Each finding was vetted through the panel's discussions in which we reached agreement on its significance within the Air Force and DoD. As we refined each finding, it became obvious that an action recommendation was needed to ensure closure. These findings and recommendations appear in this section and throughout the report in the area where the finding will have the greatest impact. The six major findings and recommendations are as follows:

FINDING AIM #1

The C^2 Vision drives the information management architecture.



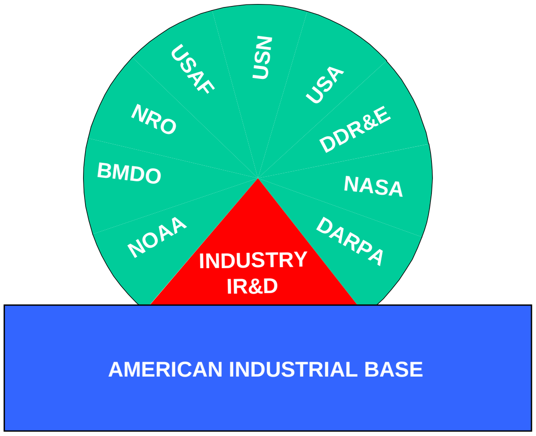
RECOMMENDATION AIM #1

Task Aerospace Command and Control & Intelligence, Surveillance, and Reconnaissance Center (AC^2ISRC) to define an information management architecture that enables an adaptable C^2 operational architecture with assured delivery.

Figure F-1. *Information Management Architecture*

FINDING AIM #2

Air Force Research Laboratory (AFRL) restructuring of the Air Force science and technology (S&T) efforts to support the drive toward "air and space" is timely!



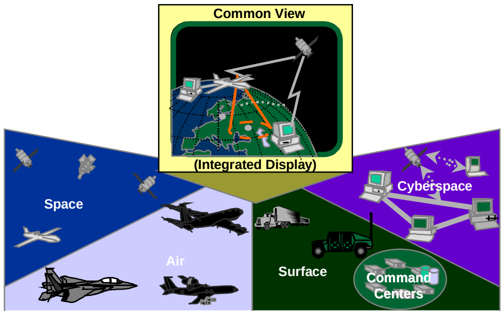
RECOMMENDATION AIM #2

AFRL should develop a partnership that enables joint planning and execution of mid- and long-range research and development (R&D) with other government organizations and the commercial industrial base.

Figure F-2. *Air and Space Science and Technology*

FINDING AIM #3

Operations must have knowledge-rich warriors for dynamic air, space, surface, and cyber environments.



The Recognized Space Picture must include
- ***Status and capabilities of U.S. space forces (to include USAF, NRO, USN, USA, NOAA, NASA, and commercial)***
- ***Status/capabilities of allied, adversary space forces***
- ***Space environment***
- ***Space threats and events***

RECOMMENDATION AIM #3

Task AC^{2}ISRC to ensure that the Common Operating Picture is synchronized with space operations and is populated with information the warrior needs.

Figure F-3. *Recognized Space Picture and Common Operating Picture*

FINDING AIM #4

Current acquisition and requirements processes are not designed to incorporate commercial capabilities across the Air Force mission areas.

RECOMMENDATION AIM #4a

AF/SC must ensure that the aerospace force robustly connects to the Defense Information Infrastructure and Global Grid and shapes the National Information Infrastructure and Global Information Infrastructure.

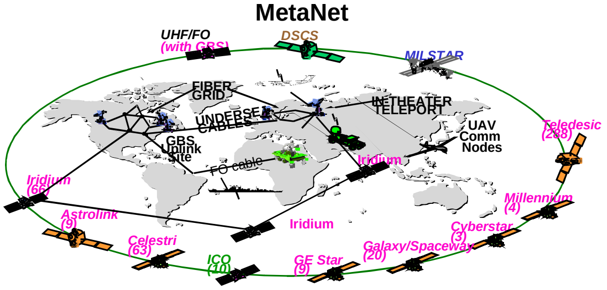
RECOMMENDATION AIM #4b

SAF/AQ should lead an effort to baseline the use of commercial systems for non-military-unique functions and implement them in a seamless, transparent, and interoperable manner.

Figure F-4. *Defense Information Infrastructure, Global Grid, and Commercial*

FINDING AIM #5

Diverse routing across multiple commercial and military communications systems and networks is essential to provide assured information delivery.



RECOMMENDATION AIM #5

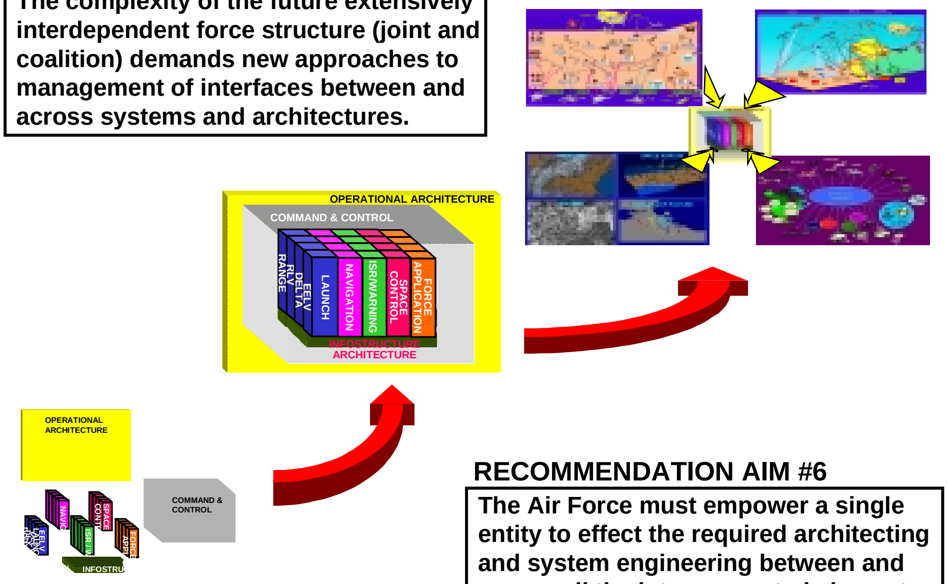
Task AF/SC to develop

- **Network access management concepts**
- **Internet protocol (IP) addressing management concepts**

Figure F-5. *MetaNet*

FINDING AIM #6

The complexity of the future extensively interdependent force structure (joint and coalition) demands new approaches to management of interfaces between and across systems and architectures.



RECOMMENDATION AIM #6

The Air Force must empower a single entity to effect the required architecting and system engineering between and across all the interconnected elements.

Figure F-6. *Architecture*

1.3 Architecture and Information Management Panel Membership

Dr. Peter A. Swan, Chair
Chief Engineer and Vice President
SouthWest Analytic Network

Dr. Thomas A. Brackey
Executive Director, Technical Operations
Hughes Space and Communications Company

Mr. Tim Bonds
Analyst
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Maj Stephen M. Matechik, Ph.D.
Senior Technical Advisor, Multi-Sensor Exploitation
Air Force Research Laboratory, Information Directorate

Executive Officer: Capt Steven R. Letch, AC^{2}ISRC
Technical Writer: Capt Thomas G. McGuire, U.S. Air Force Academy

2.0 Aerospace Force Structure and Architectural Approach

The complexity and extent of the systems architectures involved in today's and tomorrow's national security environment dictated the adoption of a consistent framework for the entire study. That framework accepts that now, and into the foreseeable future, systems can be considered neither in isolation from each other nor from the architectures they compose. Beyond that, architectures can no longer be considered in isolation from other architectures with which they interface. This key concept not only has significant technical implications, it also has a potentially tremendous impact on the way we program, budget for, and operate systems.

In addition, the recommendations should shape actions that can easily be integrated with the rest of the U.S. national security effort. Because our systems, decision makers, and military operators will necessarily have to be massively interconnected by a common information environment, our national security in the 21st century will rest on a robust, scalable information infrastructure, communications, and networks foundation. This interconnectivity will be not only between people, but also between people and machines—including weapons, their delivery mechanisms, and their associated support elements. Without such interconnectivity, timely recognition of emerging threats, and their subsequent neutralization, could be easily jeopardized. Toward that end, several elements of the DoD are working to develop mechanisms to ensure that the department's command, control, communications, computers, intelligence, surveillance and reconnaissance systems become fully interoperable. Important examples include the DoD C^4ISR Architecture Framework, the Joint Technical Architecture, and the Defense Information Infrastructure Common Operating Environment. This study has adopted a similar framework. Figure F-7 depicts this framework.

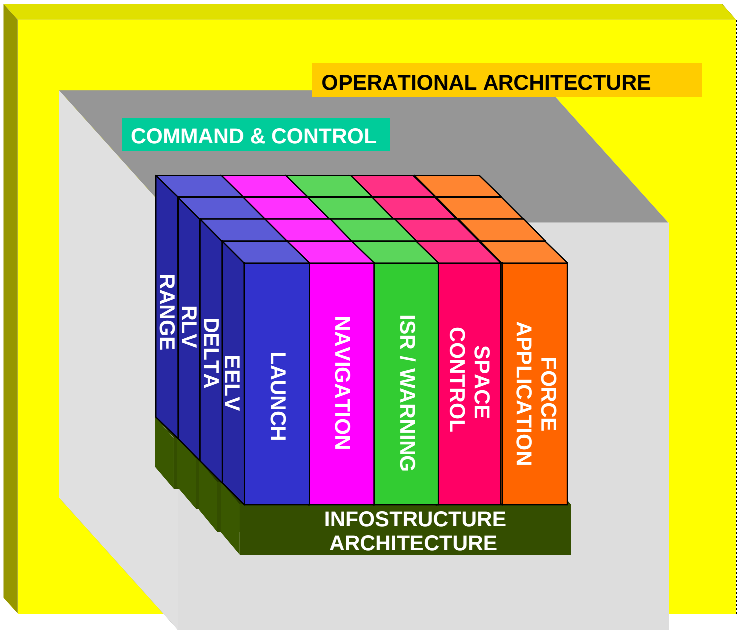


Figure F-7. *Architecture Framework*

The architectural framework includes

1. An "operational architecture" that identifies essential nodes in some operationally relevant context and the interconnectivity between those nodes. It also defines essential elements of information related to that operation and attributes of that information.
2. "Systems architectures" that provide the technical system response to the operational need in terms of physical characteristics and performance parameters. The framework includes multiple system architectures that themselves comprise several systems.

The framework includes four key components: first, an "infostructure architecture" foundation in recognition of the fundamental role that information plays in our current and future national security enterprise; second, functional system architectures such as "force application"; third, an overarching C^2 architecture that drives the previous two architecture types to respond across their interfaces as required by the operational architecture—the fourth component—in response to operational needs. These needs transcend the tactical domain to include the operational and strategic elements of our national security processes.

Although force application; space control; intelligence, surveillance, and reconnaissance (ISR)/warning; navigation; and launch serve as the functional system architectures for this study, the most important characteristics of the framework are the notion of an infostructure foundation and the importance of the interdependency between and across the elements of the end-to-end architecture of architectures. These functionalities were chosen as a result of a review of existing work that has been accomplished by the Air Force Space Command, Air Combat Command, and others.

Note that each of these architectures must be considered in the end-to-end context of the systems that compose them. In the case of the ISR/warning architecture, these constituent systems would be tasking, collecting, processing, analyzing, and disseminating (see Figure F-8).

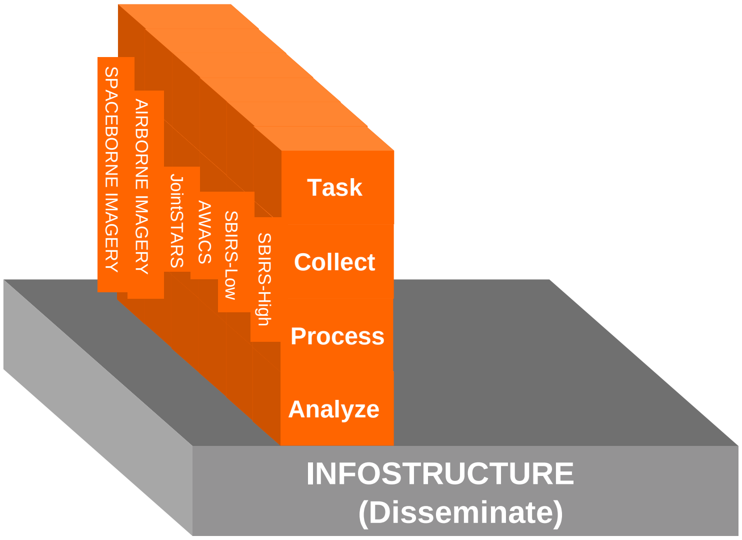
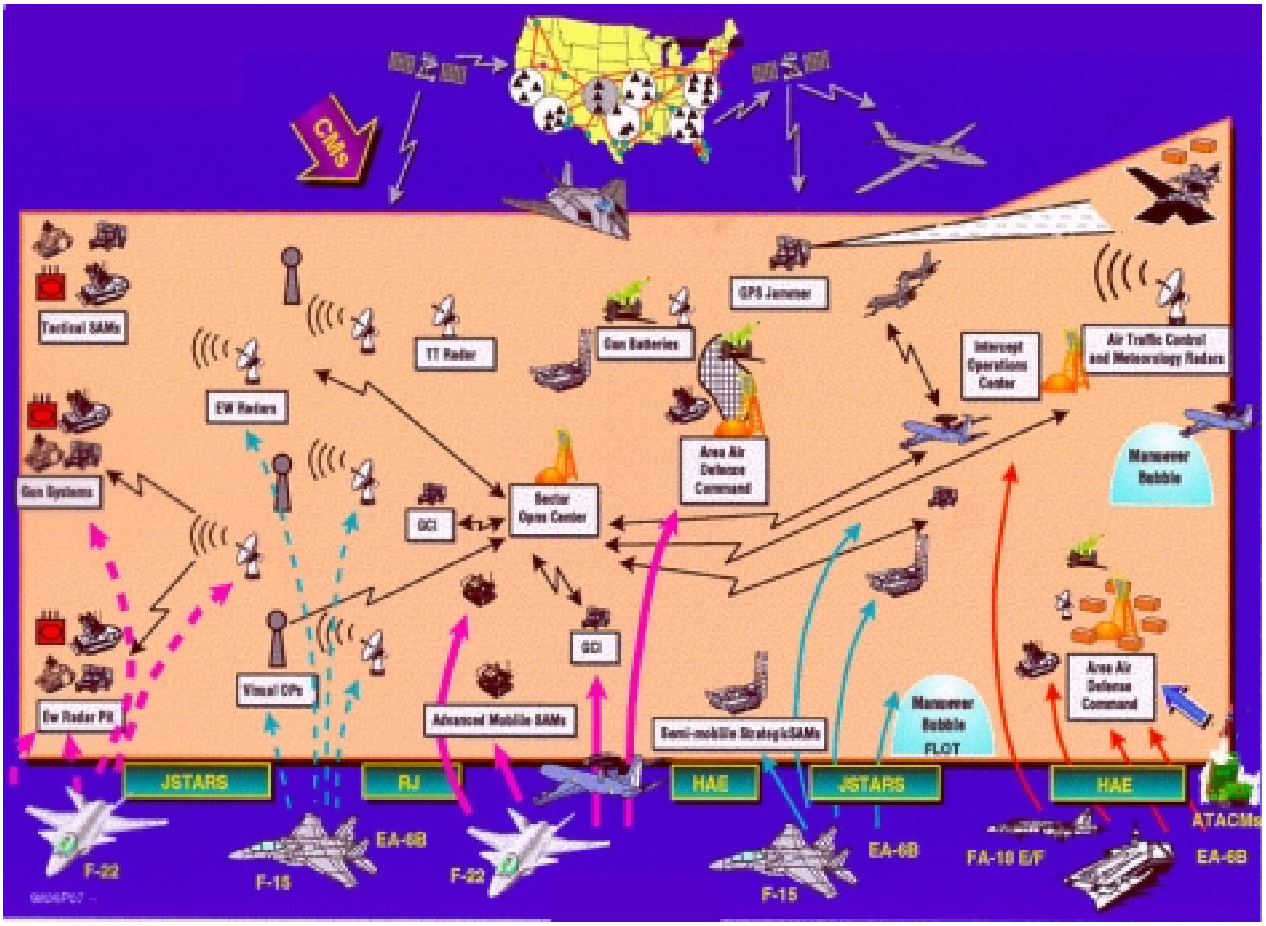


Figure F-8. *ISR and Warning Architecture*

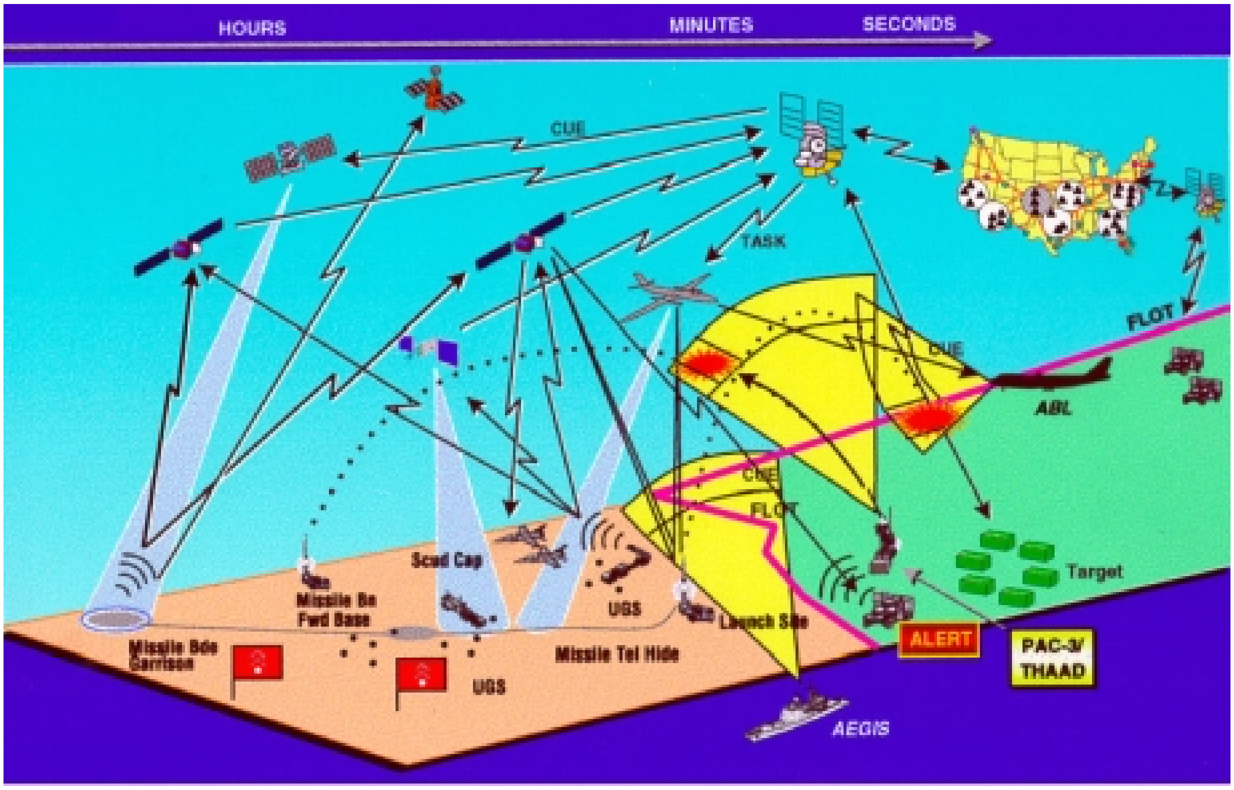
Each of these elements is essential to meeting the mission goals. A change to one element without understanding and responding to the impacts on the others will cause significant, possibly unacceptable, degradation of the whole. This interdependency is not new, but recent technological advances and future operations tempo require new technical and cultural paradigms when it comes to how we conceive, design, acquire, field, and maintain systems.

The basis for understanding the mission-essential tasks these architectures are required to perform is rooted in the uniform Joint Mission Element Task Lists and their correlation to the Air Force Minimum Essential Task List and core competencies. However, it is essential to place these in an operational construct to test the hypotheses about the needed future functionality. Tasks in isolation from an operational construct do not provide the essential basis to understand the interaction across architectural and system interfaces. Toward that end, this panel chose to leverage off the tremendous level of effort that DoD and the intelligence community have invested in developing operational concepts for Joint Suppression of Enemy Air Defenses (JSEAD) and Joint Theater Air and Missile Defense (JTAMD). It was important to use at least two of these concepts because whatever functionality is made available, it will be required to meet a broad spectrum of operational challenges. These two concepts embody what we believe is representative of the operational tradespace boundary that will test the resilience and dynamic range of our future force structure in individual, joint, or combined situations. Graphical representations of the JSEAD and JTAMD operational architectures are in Figures F-9 and F-10 respectively.



Data/Info Flow	Data/Info Characteristics				
	Capacity	Timelines	Quantity	Accuracy	Age of Data
C^2					
Tasking					
Data/Info					
Engagement					
Logistics					

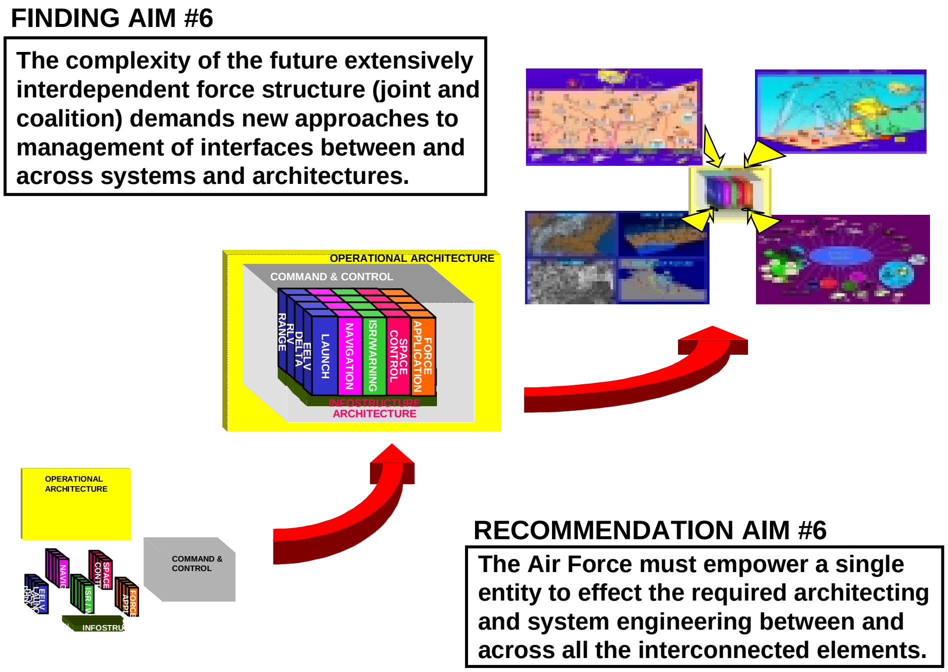
Figure F-9. *Exemplar JSEAD Operational Architecture*



Data/Info Flow	Data/Info Characteristics				
	Capacity	Timelines	Quantity	Accuracy	Age of Data
C^2					
Tasking					
Data/Info					
Engagement					
Logistics					

Figure F-10. *Exemplar JTAMD Operational Architecture*

Beyond the operational concept, we also needed to understand the type of information, and its characteristics, that operational commanders need to perform these tasks. For that, we turned to the Assured Support to Operational Commanders document.



FINDING AIM #6

The complexity of the future extensively interdependent force structure (joint and coalition) demands new approaches to management of interfaces between and across systems and architectures.

RECOMMENDATION AIM #6

The Air Force must empower a single entity to effect the required architecting and system engineering between and across all the interconnected elements.

Figure F-11. *Architect*

Table F-2. *Air Force Architect*

Finding AIM #7: The approach to 21st-century warfare requires a 21st-century organization that transforms suboptimized architectures, mission solutions, and resource allocation. There is no Air Force champion/Office of Primary Responsibility/focus that can drive the air, space and C^2 solutions.

- **Recommendation AIM #7a:** The Air Force must organize to capitalize on the emphasis toward integrated planning, requirement generation, and resource allocation across all Air Force missions (work with Gen Moorman on his study for Air Force reorganization).
- **Recommendation AIM #7b:** Create an Air Force Systems Architect within the Chief's Office to evaluate across fiefdoms. An example: Integrating a robust Global Positioning System (GPS) and augmentation into the Air Force force structure will enable a revolutionary Air Force capability. GPS is the enabler for precision targeting, precision weapon delivery, fusion of data, and synchronizing communications.
- **Recommendation AIM #7c:** Create an Office of the Aerospace Architect responsible for system-of-systems issues within the Air Force and across the national security missions. (An example: Digital programmable receivers will allow the Air Force to exploit many new opportunities for providing future information systems into their force structure at small costs. It is a crucial building block of information warfare. It is a particularly critical enabler for mobile platform capabilities in the future.)
- **Recommendation AIM #7d:** "Always Joint, Sometimes Combined"—Space systems should be treated as force structure, not as space; they can offer dramatic new capabilities in old functions of targeting, weapon delivery, intelligence, bomb damage assessment, information, and communications. Technology offers dramatic new opportunities, even though the principles of war have not changed.

3.0 Information Management Philosophy

3.1 Information Management in the Military Environment

For the majority of humanity's time on earth, land and the possession of it have been the chief equity for a national economy. Taking or possessing land was the essence of war. As agriculture yielded to industry, war too became more industrialized. Nations defeated nations by destroying their opponents' industrial complex and therefore their ability to wage war. If we assume that this stratagem holds true for the information age, then we must consider that the next major war will be waged partially in cyberspace, pitting foe against foe, not for land, but for control of cyberspace and the critical information it contains.

Some might argue that we have already fought a war where information was king and the application of power based on critical information handily won the day. With its victory in the Gulf War, the United States demonstrated an unprecedented mastery of conventional warfare. Indeed, it has been heralded by many as the first "space war." The critical questions now are "What did we learn from the Gulf War experience?" and "Can we put our 'lessons learned' into action in preparing for the next conflict?" The U.S. military complex has some tough decisions to make. Do we continue to produce conventional military systems that take advantage of our existing information infrastructure and update them as necessary, or do we really look into the future and realize that information is the key to all future conflicts, and plan accordingly? If indeed one concludes that information management is and will continue to be the prime equity in future conflicts, then one must also conclude that any system not making use of or adding to one's information dominance is out of date and needs to be replaced. Merely replicating today's weapons in a more capable form is just a stopgap measure. Granted, some duplication is warranted in order to maintain the information dominance advantage, but essentially the whole military-industrial complex is undergoing a momentous shift in capability. The key to this capability is information management and the ability it provides for an informed military force to operate inside the enemy's information/operation cycle. Recent real-world events, significant exercises, and extensive modeling and simulation have shown that once we are inside an opponent's information/operations cycle, we are free to act, almost with impunity. There have been tremendous improvements in U.S. military capabilities in the past few years, arising mainly from simultaneous developments in the following areas: battlespace awareness; advanced command, control, communications, computers, and intelligence (C^4I); and precision force derived again from ISR. Some of the hardware developments in these areas come from prudent investments made in the 1980s; others were spurred by the Gulf War, but the most important developments are just now being realized, and they lie in the areas of information management to advance the warfighter's knowledge.

Battlespace awareness: For the past several years, electronic advances have provided battlespace awareness via digital images and bit streams from atmospheric platforms such as the Airborne Warning and Control System (AWACS) and the Joint Surveillance, Target, and Attack Radar System (JointSTARS). These systems are very ably aided, in large part, by space-based systems both for collection and distribution. In the future, both the AWACS and JointSTARS missions will be performed from space and supplemented by unmanned aerial vehicles for close-in air support and information dissemination. Historically, battlespace awareness has provided commanders with information on large groups of tanks or airplanes with general, and sometimes fairly precise, information concerning heading and speed. However, with some current systems, and certainly with future systems, such as ground moving-target indicator technology, commanders will receive latitude and longitude coordinates combined with speed and altitude information for each target and the capability to instantly pass that information to a precision-guided munition (PGM), with deadly effect.

C^4I and ISR: Today, and certainly in the future, it is and will be impossible to think of a battlespace that is not defined by C^2 centers and communication and intelligence nodes, all linked by computers to an

information grid that not only processes information but uses artificial intelligence to aid commanders in their decision-making process. These enhanced capabilities will allow commanders to receive information from and send processed information (knowledge) where it is needed most, in real time.

Precision force: In the distant future, wars may be fought mainly with information resources, and the information-dominant state will emerge the victor. Certainly this is a humane and noble state of affairs to aspire toward, but for the foreseeable future wars as we know them will depend not only on information but to some extent on PGMs. Information management will be absolutely critical to ensure that the munition hits its target. Even today, PGMs can put any locatable target at a high risk of destruction. Most targets can be dispatched with one shot; few can withstand a volley. Even though a significant part of the PGM revolution has already occurred, PGMs continue to advance along three lines: human-guided weapons (such as fiber-optic-guided missiles and laser-guided bombs); signature-guided weapons (such as those guided by infrared, radar reflection, or acoustic homing); and location-directed weapons (those that know their exact coordinates and the exact coordinates of the target, usually via a combination of GPS and a backup inertial guidance system). The latter category of weapons has also allowed us to develop user-friendly weapons that are better known as long-range stand-off weapons and fire-and-forget weapons. Again, both types usually rely on GPS and inertial systems. This long-range strike capability would be of less value without critical information technology presented to the warfighter in a timely way. When the PGM and the information to target it are combined, this awesome capability allows U.S. military forces to target and destroy enemy platforms while operating beyond the reach of enemy weapons and sensors. This capability arises not only from accurate, long-range missiles but also from platforms that can operate far from their bases (such as refueled aircraft) or remain on extended station. Because technologies of range (jet and rocket engines, cruise-missile motors, and nuclear reactors) tend to be expensive and improve rather slowly, the U.S. advantage in this area is relatively secure. This contrasts with much of the U.S. lead in high-tech weaponry, which is based on information technologies' advancing ubiquitously at the same rate. In fact, most experts agree that in 2020, if not sooner, our adversaries will essentially share the same high ground of space with the U.S. and its allies, but they won't necessarily share the critical knowledge concerning integration of technology and weapon systems that will enable the United States to maintain a dominant position in the world.

Conclusions: What has been described here can be construed as the battlefield of the future or the future environment for information management leading to information dominance of the battlespace. However the previous discussion is labeled, it is important to realize that it all centers on the optimal use of information. We have concluded that this is a fail-safe strategy, but there are others who are not so sanguine. Robert K. Akerman from Georgetown University writes, "There is considerable debate over whether the injection of information technologies into defense systems can provide a basis for undertaking a revolution in military affairs (RMA). One good test is whether a new instrument of power is indeed revolutionary—whether it can alter relationships among states. Ancient innovations, for instance, shifted the balance of power back and forth between dismounted and mounted forces, and, consequently, between civilized and barbaric cultures. The advent of gunpowder doomed the isolated city-state. Napoleon's *levée en masse* redrew the map of Europe, setting off nationalistic reverberations that echoed for the next century. The Third Reich's blitzkrieg ushered in new forms of international coercion. And nuclear weapons, originally conceived as a force multiplier for conventional operations, may have had the reverse effect; they made conventional conflict among nuclear powers a potential first step to mutual suicide and hence of sharply decreased utility. Whether or not the new military applications of information technologies constitute a true RMA will therefore depend on the new uses to which a military so equipped can be put." So it appears that our biggest challenge is not in using new technology and the information it provides but in freeing ourselves from the power of old processes. We need to understand how the battlespace of the future will operate, determine how to be the world's most efficient operators in that environment, and be willing to adopt those practices that best ensure mission success.

Table F-3. *AIM Findings and Recommendations*

Observation AIM #8: The integration of space (and information sphere) operations into the Air Operations Center must be accelerated.

Finding AIM #8: The status of U.S. space forces—to include the Air Force, National Reconnaissance Office (NRO), Navy (USN), Army (USA), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and commercial—must be visible and operationally current to ensure that the battlespace commander knows that "the top cover" is "green."

- **Recommendation AIM #8a:** Develop concepts that provide combatant commanders with an integrated warning of enemy attacks or other operations exploiting the air, space, or cyber environments.
- **Recommendation AIM #8b:** Provide combatant commanders with the health, operational status, and capability of all U.S. and allied forces exploiting the space environment.
- **Recommendation AIM #8c:** Provide combatant commanders with the ability to heal gaps in all capabilities by reconfiguring military systems or selectively bringing into play commercial systems.
- **Recommendation AIM #8d:** Provide combatant commanders with systems that provide health, operational status, and capability of commercial imagery, communications, or other information needs.
- **Recommendation AIM #8e:** Provide combatant commanders with displays that show alternative end-to-end concepts (such as communications links).
- **Recommendation AIM #8f:** Invest heavily in war games and in exercises to demonstrate the potential of new communicative means and information-rich warfare to revolutionize Air Force capabilities. Fund aggressively innovative ideas to be tried with new operational concepts in the exercises.
- **Recommendation AIM #8g:** Demonstrate through modeling and simulations, war games, and exercises new information management technologies and systems to revolutionize Air Force warfighting capabilities through knowledge-rich warfare.
- **Recommendation AIM #8h:** Assure seamless, transparent, interoperable C^2/battle management with the national, military, civil, and commercial information infrastructures through utilization of space and terrestrial-based communications, remote sensing, and navigation.
- **Recommendation AIM #8i:** Conduct joint space and information management planning and program execution for mid- and long-range research and development (R&D) with the USN, USA, United States Marine Corps (USMC), NRO, NASA, Ballistic Missile Defense Organization (BMDO), Defense Advanced Research Projects Agency (DARPA), Director of Defense Research and Engineering (DDR&E), and industry.

3.2 Information Management Concept

The current systems, which collect, process, exploit, and disseminate data and information, will ride on a Global Grid of common joint communication means of greatly increased capacity. The technology of all forms of communication information systems is rapidly approaching an affordable Global Grid. Space communications system will provide a link to mobile and easily relocatable platforms, letting commanders interoperate seamlessly with a common operational picture (COP) anywhere in the world with reachback to staffs and resources in the continental United States (CONUS). The planning functions of the commander will be based on direct feeds from air and space ISR. Common tagging of data with precision position and time will allow a common representation of real-time and historic data. The development of means to establish the credibility and validity of sources and authorized analysis sources will provide information superiority and shorten the planning cycle to hours or minutes instead of days. Major considerations for gaining information superiority are

- We must maintain focus on the customer—commander-to-shooter.
- Global awareness and C^2 enable the aerospace force to have information superiority for global engagement.

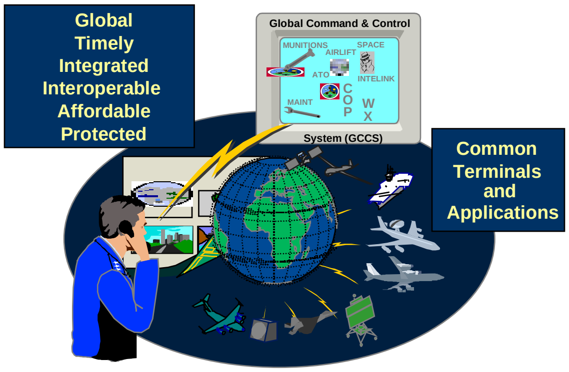
- The future joint force commander will have an integrated global and theater air, space, and surface picture of the battlespace.
- The final step is the presentation of information in command decision format for all echelons and functions.
- Decision makers' needs will drive information collection, processing, exploitation, and dissemination.
- The commander will be able to tailor the information and updates by preformatted means to enable the force structure to operate with adequate mission data and updates in near real time as needed.
- The commander will be able to target and task aircraft en route. The air and space tasking orders can evolve to shorter and shorter time scales and allow a mission structure with dynamic retargeting.
- The integration of GPS is creating a revolution in military capabilities to provide precision location of Blue forces and precision targeting and all-weather delivery of standoff weapons. Submeter capabilities will become feasible.
- Air operations will precisely synchronize in space and time, reducing air traffic control issues as well as allowing all-weather operations.
- Satellite communications will allow mobile platforms such as AWACS to move without a ground infrastructure, leave some of the staff on the ground, and have beyond-line-of-sight C^2 capabilities to other mobile force structures.
- The shooter can receive adequate updates and battlespace awareness as decided by the commander. Large data rates are not necessarily needed by smaller mobile forces. Space mobile communication systems will allow low-data-rate communications into any platform at affordable prices.
- The commercial communications and information technologies and systems provide most of the building blocks to supply the Global Grid and communication to mobile platforms. The challenges are implementation of these technologies, developing integrated ISR systems, and learning how to provide decision-based information at all levels.
- The aerospace force can provide a new dynamic of rapid, lethal force that will be an important addition to national security and conventional deterrence.
- The potential revolution in military technology will require a change in culture and in our way of doing business, and dynamic partnerships with the commercial and scientific communities.
- Fortunately, the Air Force is a high-technology organization that has always worked with scientific and technology partners in industry and academia.

3.3 Information Management Vision

The Air Force requires an information management architecture that allows it to realize the full potential of aerospace power capabilities. Information management touches upon a host of important military needs ranging from ISR to C^2. Each commander will tailor the architecture envisioned in this report to specific mission responsibilities. The architecture will integrate information from global and theater assets, both inside and outside the Air Force, and enable seamless C^2 of forces around the globe. In addition, it will exploit commercial technologies to satisfy technological currency and affordability. A cross-organizational vision will enable the full Air Force information transfer and information management teams to work for a common goal.

FINDING AIM #1

The C^2 Vision drives the information management architecture.



RECOMMENDATION AIM #1

Task Aerospace Command and Control & Intelligence, Surveillance, and Reconnaissance Center (AC^2ISRC) to define an information management architecture that enables an adaptable C^2 operational architecture with assured delivery.

Figure F-12. *Information Management Architecture*

The future information architecture will include elements based in space, in the air, or on the surface of the globe. Many of these systems may be operated by the military Services of the United States or by its allies or coalition partners. The majority of systems, however, will be operated by commercial companies headquartered in the United States or allied nations. In many cases, these will be international companies with operations around the globe. More important, these systems together will form a vast and vastly complicated information network upon which the Air Force information management architecture will operate.

3.4 Employment of Aerospace Power

The information management architecture recommended in this report is intended to advance Air Force military capabilities. Modernization efforts are intended to improve the contribution of military forces to the missions given to combatant commanders by the National Command Authority (NCA) to underwrite the national military objectives. The architecture must provide whatever connectivity and information flow are needed to maximize the contribution of the Air Force to military missions. The architecture must not be a bottleneck, limiting the flow of vital information. Instead, it must be a key enabler of new operational concepts for the employment of aerospace power.

Table F-4. *AIM Observation, Finding, and Recommendations*

Observation AIM #9: The core issue in all architectural and informational management concepts must include an understanding of what information should be transferred (pushed or pulled) to the platform or node, with answers for when, in what format, and for how long.

Finding AIM #9: The Air Force operations for the 21st century must have knowledge-rich, hardware-capable, superbly trained warriors prepared to succeed inside a dynamic hostile air, space, and cyber environment.

- **Recommendation AIM #9a:** Ensure that air, space, and cyber operations are interoperable and integrated across the Air Force and within the joint and coalition forces.
- **Recommendation AIM #9b:** In addition to the historic mission battlefield management, the commander's C^2 assets must also manage the information sphere necessary for the commander's success.

4.0 Information Management Structure

Successful C^2 depends on the timely exploitation of relevant information. Commanders rely on information to depict the battlespace, detect attack, determine adversary intent and capabilities, and then direct the appropriate maneuver and positioning of commanded forces. This critical reliance on information underwrites the *Joint Vision 2010* tenet full-spectrum dominance and is the basis for the Air Force's Global Engagement goal of Information Superiority. Achieving information dominance mandates universal connectivity between deployed forces, Commanders in Chief (CINCs), the NCA, and supporting elements, including coalition forces. Information dominance, especially its C^2 aspect, generates huge demands for communications bandwidth. The expeditionary Air Force (eAF) adds the further requirement that necessary bandwidth be available within any region on short notice. The Global Grid provides the bandwidth and other communications functions to support the eAF mission and information dominance.

4.1 Communications—The Vision

The need for connectivity between military forces is all-pervasive. It is the glue that connects the elements of the C^2 process, and the enabler for force application. It provides for the intelligence preparation of the battlefield, it provides for the critically needed logistics support, and it passes battle damage assessment information. It is used for planning, for execution, and for administrative matters.

But, for many reasons, communications requirements have skyrocketed in the military environment. What has really occurred is that there has been a huge increase in the resolution and coverage area of our information-gathering sensors, which has resulted in

- A major increase in the processing power to prepare, disseminate, understand, and display information, which has resulted in
- An explosion in the volume of information desired in the conduct of U.S. military operations, which has resulted in
- Unrealizable requirements for communications capacity and joint/coalition interoperability, which has resulted in
- Leadership's concern for how the needs will be satisfied

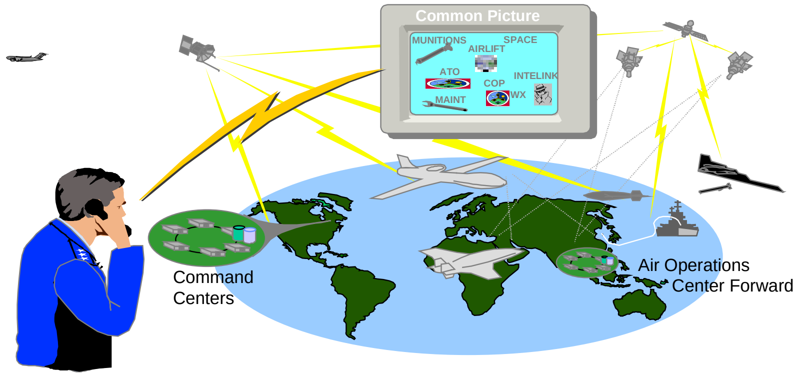
On the other hand, and for very different reasons such as banking and entertainment, commercial communications needs have also increased tremendously and, with them, commercial capacity.

The result has been that the commercial and military worlds have had to view communications in a new way: the network or infosphere approach. This has several important implications for the Air Force and, for that matter, the military in general:

- The military must view the communications system as a network, actually a network of networks, which includes all Air Force elements and other warriors as well. In general, this is not now done.
- The Air Force needs a flexible information architecture, functionally and physically, that can serve its needs.
- The demand must be made consistent with the need, and the need must be made fiscally responsible and consistent with the transition from mostly person-to-person (voice) communications to mostly computer-to-computer (digital) communications, the latter being orders of magnitude more efficient.

4.2 Global Grid

The Global Grid is the fundamental enabler for global awareness and dynamic aerospace command. It provides the pathway for the transmission and protection of C^2 data and information. The Global Grid is just that—a grid of connected communications systems that makes possible global connectivity for C^2 elements and organizations. Functionally, the Global Grid uses the capabilities provided by defense, national, commercial, and coalition communications resources. The Global Grid is necessary to enable the communications that build the foundation for dynamic aerospace command. Lean and mean eAF operations will demand that C^2 be distributed and collaborative. Virtual battlestaffs, as they are now envisioned, will serve as the central elements in future C^2. Force and funding constraints, coupled with the evolving geopolitical picture, will limit the size of forces that move into the conflict area. Deployment forces will be smaller. These smaller forces will depend heavily on rear-based force support elements for information, intelligence, planning, and sustainment. Essentially, future conflict will involve sensors and shooters forward with support elements located far to the rear, often operating from their peacetime operating locations as depicted in Figure F-13. This operational paradigm will require the transmission of far more information than is currently necessary or possible. Increased information volume will mandate improved connectivity using substantially more bandwidth.



The Global Grid represents the communications and data infrastructure needed to command and control forces supporting dynamic aerospace command. The Global Grid relies on an integrated infrastructure of defense, national, commercial, and international communications and data systems to support deployed forces dependent on command centers located to the rear, often in CONUS. In this context, the Global Grid provides a shared COP through protected, high-capacity links and enables anywhere, anytime C^2 connectivity.

Figure F-13. *Command Picture*

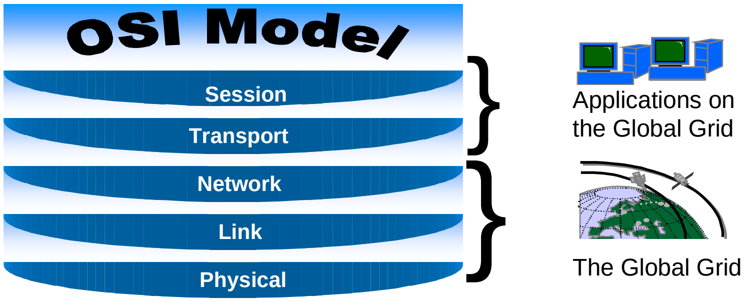
Improved connectivity—through the Global Grid—is the fundamental enabler for the eAF operational concept. The Global Grid will provide protected global, anytime, anywhere connectivity. The Global Grid will provide C^2 connectivity across the full spectrum of military requirements: peacetime readiness, deployment preparation, deployment, employment, sustainment, and reconstitution. The Global Grid will enable reliable, continuous, protected, and redundant service to the strategic force elements and the NCA. It will facilitate aggregation and dissemination of the integrated COP of the battlespace to the Joint Force Commander (JFC), supporting theater forces, and the NCA. During peace and war, the Global Grid will enable continuous contact between operating entities and command, whenever, wherever.

The Global Grid will enable distributed, collaborative functions. It will support establishing a virtual staff—that is, a staff that is geographically separated but electronically connected so that it functions as if its members were collocated. For example, if a function is performed largely by computer or through a communications connection, that function can be performed well behind the battle area, in many cases from locations in CONUS. Thus, the JFC, the Joint Forces Air Component Commander, and the other battlespace commanders will rely on support—that is, the provision of information—from rear-based elements. Increasingly, intelligence information, capability forecasts, monitoring and assessing mission execution, and control of airborne resources (for example, the tactical C^2 system) will originate in the rear, with the operators geographically separated from but plugged into the Battlespace InfoSphere. Video teleconferencing, electric white boards, and other technologies will maintain the psychology, efficiency, and satisfaction of face-to-face contact. Improved communications, displays, and cognitive-driven systems will enable the distributed staffs to function ever more effectively.

In its role as the executive agent for battle management, the Air Force must focus extensively on information dominance in its broadest context. The Air Force must ensure that information exists where needed, when needed, anywhere in the world and at every echelon of command. This same requirement is the foundation for global awareness and its ultimate manifestation: the ability to find, fix, track, target, and attack any threat anywhere on the globe in time to warrant the intended effect. To meet these challenging requirements, the Air Force must maintain an intellectual and fiscal commitment to the development and maintenance of Global Grid capabilities, most notably the acquisition of bandwidth and development of compatible systems.

The Global Grid relies on the combined capabilities provided by the Defense Information Infrastructure (DII)—particularly the Defense Information Systems Network (DISN)—the national information infrastructure (NII), and the commercial information infrastructure. In other words, the Global Grid is the arrangement of all available communications systems, DoD and otherwise, to collect, fuse, and transfer information where needed, when needed, worldwide. Initially, the Air Force will focus on the Global Grid as a connectivity mechanism for the transport of data. This concept aligns with the lower layers of the Open System Interconnection (OSI) model, the standard reference for depicting information systems elements, as depicted in Figure F-14. This panel recognizes the MetaNet concept as meeting these expectations (see Figure F-15 for a MetaNet graphic).

The Open System Interconnection Model and the Global Grid: A delineation of function



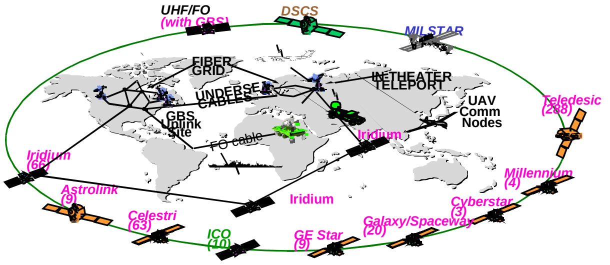
The Global Grid encompasses the Physical, Link, and Network layers of the OSI reference model. These layers include the physical infrastructure (wires, electromagnetic transmissions, lasers, etc.) and the networking mechanisms that control the transmission of the data. Applications, such as those in the command centers, ride on top of the Global Grid. Eventually, the Global Grid will expand to include some applications, especially those that facilitate COP generations.

Figure F-14. *OSI Model*

FINDING AIM #5

Diverse routing across multiple commercial and military communications systems and networks is essential to provide assured information delivery.

MetaNet



RECOMMENDATION AIM #5

Task AF/SC to develop
- **Network access management concepts**
- **Internet protocol (IP) addressing management concepts**

Figure F-15. *MetaNet*

The challenge of providing Global Grid services is daunting. Diverse systems owned and operated by a wide range of sources—Government and commercial—must work harmoniously to transfer and protect data reliably and quickly. Meeting this challenge will require the design and implementation of communications and computer systems that adhere to common standards. The Defense Information Infrastructure Common Operating Environment (DII COE) establishes the near-term interoperability requirements for systems development. In the longer term, implementation of the Shared Data Environment (SHADE) will define the necessary standardization of data. The test of the Global Grid will be the ability of an organization to deploy forces to a bare-base location and maintain all necessary C^2 connectivity continuously before, during, and after the deployment. Reaching this objective will require C^2 systems that are compatible with available communications systems anywhere in the world, a landscape that is changing rapidly.

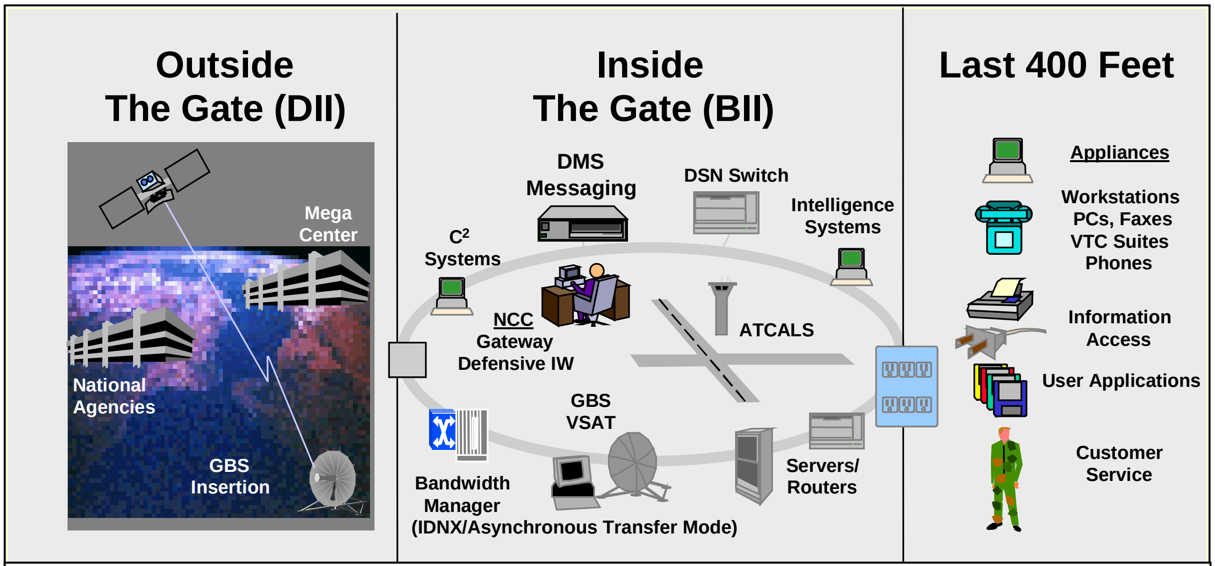
Part of the requirement to access greater bandwidth will be met by greater reliance on emerging, next-generation satellite constellations. These systems employ multiple satellites that provide simultaneous global coverage. Some of these systems will use satellite clusters that operate in low earth orbits. Others employ middle earth orbits or geosynchronous orbits. These new satellite systems are only part of the new technologies that will enable Global Grid functionality. Most of these systems are commercial. They adhere to commercial standards that may not reflect military specifications. Commercial standards will drive the design of new military systems even to the extent that more systems will be procured off the shelf rather than through specific military design. As the adherence to commercial standards expands, the significance of military specifications for Global Grid components and those systems that rely on Global Grid connectivity will diminish.

The Global Grid must provide plug-in connectivity. An operator, whether a Special Operations Force team in a clandestine field location, a fighter squadron at a main operating base, or a C-17 crew at a distant commercial airfield, must be able to connect to the centralized C^2 functions and other service entities via whatever communications infrastructure exists. These facilities will vary from handheld systems to commercial telephones to direct DISN hookups. C^2 systems must be interoperable with all of these connections and more in order to be Global Grid–compliant. Connecting to the Global Grid must be easy. Not only is connectivity from anywhere, anytime a basic requirement, the mechanisms that facilitate this connectivity must be simple to use, small, efficient, and reliable. Future eAF deployment packages will be smaller and lighter. These smaller deployment packages will demand smaller equipment. Instead of carrying dedicated communications equipment, these packages must rely on equipment embedded within the Global Grid.

The Global Grid must be smart. It must include tools that automatically control network routing and load balancing. The eAF will force new, large requirements for bandwidth at remote locations with little advance warning. The Global Grid must automatically sense this need and reconfigure resources to meet the demand. The Global Grid also will be self-configuring and self-healing. It will be redundant and protected. It will detect attack, defend against attack, compensate for attack, and notify users of attack damage and effects.

The Global Grid's reliance on commercial services for part or all of its bandwidth will increase its vulnerability. It may be especially susceptible to interception, jamming, and interference. Protection against enemy action as well will mandate increased use of encryption. Moreover, the Global Grid will need multi-routing capability for high-priority traffic. The Global Grid must handle traffic with varying priorities and provide precedence to the most important. The significantly increased bandwidth required from eAF operations will challenge the Global Grid's ability to maintain throughput. To ensure that the message gets through, the Global Grid must provide mechanisms to prioritize traffic according to importance. Some messages—attack warnings—must get through immediately. Other important messages must get through but can take a little longer—for example, supply requisitions. Even though the Global Grid may be temporarily saturated locally, its self-configuration capability must quickly tailor components to provide the bandwidth necessary to handle all throughput requirements.

The Global Grid will rely on an infrastructure composed of commercial and military systems to provide the connectivity needed to support anytime, anywhere C^2 for DoD and coalition or allied partners. The DoD leg of the Global Grid will be the DII (see Figure F-16). Broadly defined, DII is the web of communications networks, computers, software, databases, applications, weapon system interfaces, data, security services, and other services that meet the information processing needs and the range of DoD operations.



The DII integrates communication from the desktop to remote operating locations. It relies on a backbone that combines defense, national, commercial, and international communications resources. DISA will integrate the total architecture and provides *Outside the Gate* functionality on a fee-for-service basis.

Figure F-16. *Global Grid Model*

Responsibility for the various parts of the DII will rest with different entities or organizations. For the perspective of this concept of operations (CONOPS), the DII will comprise three integrated entities: Outside the Gate, Inside the Gate, and the Last 400 Feet. Together, these parts will provide connectivity for the Global C^2 network, a collection of interoperable systems and applications that facilitate C^2 by adhering to a common architecture defined by the DII COE.

- Outside the Gate (long haul). The Global Grid will rely on the DII to provide connectivity over long distances primarily using the DISN. Outside-the-Gate functions include long-haul connectivity and computer megacenters. The Defense Information Systems Agency (DISA) is responsible for Outside-the-Gate functions. DISA establishes the standards for the systems and applications that provide the common carrier functions. DISA provides Outside-the-Gate functions on a fee-for-service basis.

- Inside the Gate (fixed bases, deployed locations). This segment of the DII lies within the base. Typically, Inside the Gate will define the base communications architecture, systems, and applications. In the near term, the Combat Information Transport System and Theater Deployable Communications programs will control this segment with funding from the supporting Major Commands. Examples of Inside-the-Gate systems include telephone switches, network control centers, satellite communications facilities, the base cable plant and its integral servers and routers, the Defense Messaging System, and air traffic control systems. Inside-the-Gate components will be compatible with the COE.

- Last 400 Feet (buildings/work centers). This segment will connect users to the Global Grid. It will consist of the local area networks, servers, workstations, printers, appliances, telephones, common-user applications, and mission-specific applications that support the user's accomplishment of the mission. Typically, the using command or agency will fund and provide this segment. Since this segment provides the user interface with the Global Grid, it will have to be available wherever users operate. Many of the components that compose the Last 400 Feet will be portable. In order to support the eAF, units will have to carry servers, workstations, and other devices to the mission area. These components will be small and eventually thin—that is, they will connect to data and applications located elsewhere.

4.3 Defense Information Infrastructure Common Operating Environment

The DII COE defines an architecture that supports interoperability across applications, data, and computer platforms. With its definition nearing completion today, the COE will mature and provide the directive basis for migrating legacy systems and building new ones. At the minimum, the DII COE provides a near-term framework for migrating and developing systems that will work together more effectively while reducing duplicative software development efforts. As the DII COE matures, it will change as hardware and software technologies develop new capabilities. The COE will provide the initial guidance to build systems that work together, and it will be the foundation for future systems development. The first systems being developed for C^2 under the DII COE include the Global Command and Control System (GCCS) and the Global Combat Support System (GCSS). GCCS includes interoperable applications that support C^2 functions. The GCSS is the target architecture for the migration of legacy combat support systems. Although they typically operate at different classification levels (GCCS is classified and GCSS is not), they are architecturally interoperable and will merge once multilevel security evolves.

COE Concept: The COE will provide the basis for developing mission applications and communications and computer systems that will work together effectively and efficiently. This concept is defined by a specification and implemented through a software kernel and reusable software components that provide common services. C^2 applications must target COE level-eight compliance to be interoperable at the data level.

COE Architecture: The COE architecture is independent of any application or mission. It defines a generic set of operating systems, databases, common functions, and standard application program interfaces. The COE implements standards specified in the DoD Joint Technical Architecture.

COE Compliance: The DoD must enforce use of COE standards on migration and new systems. Compliance will be phased to allow time to migrate existing systems. The DII COE Runtime Specification will mature over time to cover all systems that support the Joint Task Force.

COE Processes: The COE must evolve as a set of processes and organizational structures to harmonize requirements and oversee migration. The organizational structure will consist of local configuration boards, the configuration control board, and the configuration review board. These organizations will promote an orderly COE development cycle. The Air Force will establish processes and organizational structures to prioritize COE development based on operational requirements and available funding. The C^2 roadmap, mission area plans, and long-term financial strategies implemented through the Program Objective Memorandum process will modulate COE development decisions.

SHADE: SHADE will provide the services and mechanisms needed to support the sharing of common data between applications (Figure F-17). SHADE will promote using repositories of standardized database specifications. It will provide a specification for establishing standard data servers that will serve multiple distributed applications. It will standardize database design, development, installation, and distribution. It will enable distributed databases to support the collaborative processes that form the heart of Dynamic Aerospace Command.

SHADE

Shared Data Environment

…strategy and mechanisms for data sharing that extends the DII COE principles. SHADE includes data access architectures, reusable software and data components, and guidelines and standards.

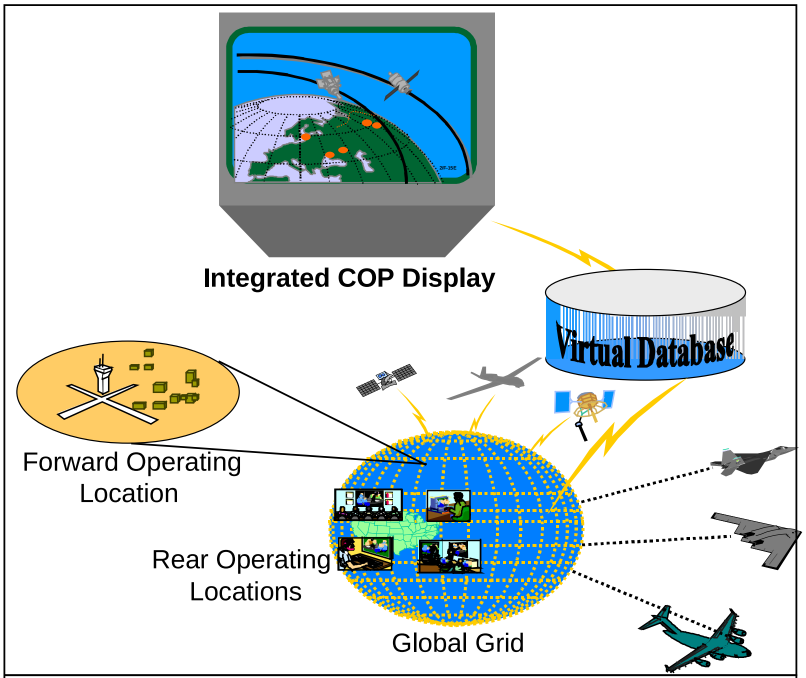
SHADE engineers data to enable systems migration and sharing

SHADE provides the architecture and strategy that will enable the sharing of C^2 data and information.

Figure F-17. *SHADE*

4.4 The Global Grid and the COP

In the near term, Air Force involvement in the Global Grid will focus on the connectivity functionality. In the longer run, the Global Grid will grow to provide more than connectivity. It will also fuse, store, and distribute information to support the generation of the COP. As Figure F-18 illustrates, the COP will grow to be more than a single perspective of the battlespace. Instead it will provide multiple views into the battlespace by warehousing, linking, and distributing all battlespace-related and supporting information. When the ensemble of information is linked and available for distribution throughout the Global Grid, individual users may generate custom views of the battlespace and related elements. Intelligent agents and smart filters will assist with the selection and display of information according to the particular user’s need. This functionality will serve users from battlefield commanders through the NCA, and it will ensure a consistent picture of the battlespace for friendly and hostile forces.

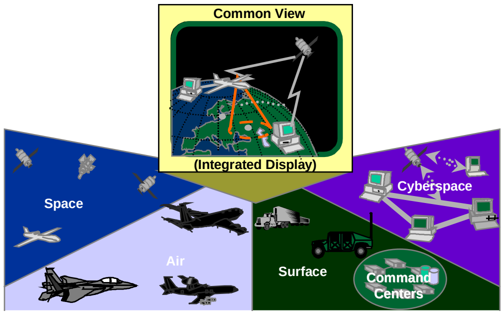


The Global Grid will grow to provide additional functionality. Eventually, it will support development and distribution of the COP through shared data in a distributed environment, a virtual database.

Figure F-18. *Vision*

FINDING AIM #3

Operations must have knowledge-rich warriors for dynamic air, space, surface, and cyber environments.



The Recognized Space Picture must include

- ***Status and capabilities of U.S. space forces (to include USAF, NRO, USN, USA, NOAA, NASA, and commercial)***
- ***Status/capabilities of allied, adversary space forces***
- ***Space environment***
- ***Space threats and events***

RECOMMENDATION AIM #3

Task AC^{2}ISRC to ensure that the Common Operating Picture is synchronized with space operations and is populated with information the warrior needs.

Figure F-19. *Recognized Space Picture and COP*

4.5 Global Grid Network Management

As defined in Joint Publication 6-02, *Joint Doctrine for Employment of Operational/Tactical Command, Control, and Communications Systems*, communications management is the exercise of systems and technical control over assigned communications resources. The functionality of communications management combines centralized control with decentralized execution, and provides efficient and effective communications support for the warfighter's information requirements. Joint doctrine also specifies the management organizations required to assist command authorities in carrying out responsibilities for the planning, employment, and operations of communications capabilities. The concepts outlined in the joint communications doctrine, however, cannot adequately address the rapid proliferation of Internet working methodologies and technology. The maturation of data communications from an autonomous and isolated local area network operations model to an interdependent and fully meshed enterprise network model requires a paradigm shift in the Air Force's approach to communications management.

The data and information required by both the warfighter and combat support elements no longer traverse a dedicated, point-to-point communication link. Gone, too, are the simplistic concepts of circuit status, circuit availability, and estimated time to repair. Today, information requirements ride a global backbone infrastructure, originating from multiple data sources, and depend upon the optimized performance and security of the various network nodes they travel, bound to their final destination. The role of communications management must now address the task of guaranteeing that information requirements can successfully migrate from source to destination. Communications management must accomplish this securely, within planning cycle constraints, optimizing resource utilization and without adversely affecting the myriad of other data and information traversing the same network nodes. This concept of providing end-to-end delivery of line-of-business applications is termed "information assurance"—the most fundamental responsibility of the communications professional. Yet nowhere in communications management doctrine is there an operational element that focuses on the mission of information assurance. There are, however, organizations that provide individual, stovepiped subsets of information assurance functionality: perimeter intrusion detection, configuration management policy, performance metrics collection, etc. Still, there is no single organization that combines all these diverse elements, producing the synergism necessary for command authorities to "fly" the enterprise network toward information assurance. Establishing a component-level Network Operations and Security Center (NOSC) answers the call for information assurance. The component-level NOSC provides the Major Command/Air Force Forces commander with a communications management entity, functioning as the focal point for collecting, correlating, and analyzing all elements to ensure that the information flows. These elements include network management, threat warning/attack assessment, mission situational awareness, and compliance with command policy and procedures.

4.6 Information Assurance

The Air Force's core competencies are information technology driven and information dependent. Aerospace operations in totality are information-intense activities. Every mission and business process depends on accurate, timely information—information that is collected, filtered, fused, and disseminated through the enterprise network. Success in the Air Force core competencies, Air Force vision, Air Force Long-Range Plan, and Air Force mission and functional processes depends on the enterprise network. Additionally, all of the new concepts, practices, and priorities—Aerospace Expeditionary Forces (AEFs), force protection, reachback, distributive and collaborative planning, precision engagement, etc.—also depend on the enterprise network. The bottom line: the ability of the Air Force to successfully execute its core competencies hinges on the professional communicator's providing information assurance over the enterprise network. A primary output of the NOSC is fact-based recommendations to the proper command authorities, for the command and control of enterprise network resources in pursuit of information assurance.

5.0 Vision for Air Force Information Management

5.1 Introduction and Context

To increase the contribution the Air Force makes to the national security enterprise and to retain its current relative advantage over adversaries, the Air Force must modernize its information management architecture. This architecture must support Air Force operations in an era of emerging political and operational challenges, expanding technical opportunities, and tightening budgets. How might political issues challenge Air Force operations? What other operational challenges may emerge? What role will emerging technologies and military funding constraints play? We will examine each of these issues in turn.

Future contingencies may thrust the Air Force into situations in which it needs to be more than usually precise in its application of force, and able to recount and describe these actions to a skeptical international audience. For instance, if a hostile nation were to build a facility to produce deadly gases or biological agents, use of lethal force might require that the Air Force strike the facility while not harming populations in proximity. In addition, the Air Force might be required to provide an international audience with incontrovertible evidence that it identified and located a hostile facility, struck it with surgical precision, and caused no harmful release of deadly agents over neighboring cities or nations.

In future operations, the Air Force may need to gather information or conduct operations while maintaining a very low profile. For instance, the Air Force might be tasked to search for subtle signs that a potentially hostile nation is preparing to build, acquire, or employ weapons of mass destruction. Any visible signs of U.S. monitoring might encourage the potential adversary to take additional security measures that might make it difficult for the Air Force to target or destroy these weapons. Or, the Air Force might be tasked to help prepare the defense of a friendly nation against attack from a hostile neighbor. The friendly nation might not yet be willing to have U.S. forces resident within its borders, for fear of provoking aggression. For its part, the Air Force might not want its activities visible to the enemy and hence giving clues as to the Air Force's operational plans or capabilities. The Air Force might be compelled to rely on out-of-theater forces early in the conflict, making it more difficult to collect information on the enemy and conduct strike operations.

Emerging technologies and systems will provide many opportunities for the military to obtain new capabilities at an affordable price. Some of these technologies will improve current warfighting capability, while others will add capabilities that are entirely new. Potential adversaries, too, have an opportunity to exploit these advances. The Air Force will need to carefully choose which technologies to support with scarce acquisition resources in order to most improve U.S. capabilities and stay ahead of potential adversaries. The tremendous growth in civilian infrastructures, such as telecommunications, may offer substantial portions of the capability the military needs, and hence may present divestment opportunities to the Air Force. Important vulnerabilities may also emerge as civil infrastructures become increasingly complex and capable.

Perhaps the biggest challenge that the future will bring is budgetary. All of the Services will need to increase their ability to meet complex contingencies with increasingly limited resources. The alternative is to face a decline in capability—which is unacceptable. The Air Force information management architecture must help increase capability in the face of limited resources.

It is the panel's assessment that many of the systems and technologies needed to meet the challenges the military faces are within our grasp. What is lacking is an Air Force strategy that focuses on investing in information rather than systems to meet specific warfighting needs. A central focus of an Air Force investment strategy should be the development of an improved information management architecture that integrates data from space-, air-, sea-, and land-based sources, is owned by commercial, military, and intelligence organizations, and provides the resulting knowledge to the warfighter.

This section will focus on three major points:

- To make best use of available resources, the Air Force needs to shift its investment focus from providing individual space systems to developing end-to-end concepts to accomplish operational tasks. The Air Force should minimize the supporting infrastructure it provides organically, acting as "steward" whenever possible and as "leader" only when necessary. An improved information management architecture should be the foundation for operational concepts that improve current capabilities and enable entirely new capabilities.
- The information management architecture must allow customized C^2 concepts for each unique commander and mission. The architecture must integrate information from global and theater assets, both inside and outside the Air Force, and enable seamless C^2 of forces around the globe.
- The information management architecture must exploit commercial technologies in order to be current and affordable. A diverse set of providers should be used to obtain supporting operations in order to obtain the greatest capabilities, robustness, and cost benefits.

Discussions about modernization options often focus on systems, without clearly articulating the military need intended to be satisfied. This may be appropriate when the military need is generally understood and we do not restrict ourselves to a particular set of systems. A subject as broad as information management, however, touches upon a host of important military needs, from ISR to C^2 of forces. Moreover, the implied military needs will change over time and as new threats emerge.

Ultimately, all modernization efforts are intended to improve the contribution of military forces to the missions given to combatant commanders by the NCA. These missions underwrite two national military objectives: *promote stability* and *thwart aggression*. In broadly stated terms, these missions appear in Figure F-20:

Figure F-20. *Missions and Critical Operational Objectives*[1]

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[1] Bonds et al., MR-905, Santa Monica, CA: RAND, 1998.

Within a given contingency, each of these missions may be supported by one or more operational tasks; examples of such tasks include

- Halt invading armies
- Neutralize enemy integrated air defenses
- Counter enemy weapons of mass destruction
- Neutralize theater ballistic missiles (TBMs) and their transporter-erector-launchers

This taxonomy is useful to help illustrate our first major point:

> The Air Force needs to shift its focus in space from providing individual systems to developing end-to-end operational concepts to support military missions.

Some would argue that the most important reason for improving the information management architecture is to enable tasks previously too difficult. Here the issue is one of *enterprise,*[2] where improved information might enlarge the Air Force contribution to military operations and capabilities. The method for solving these problems is to develop new operational concepts, which consist of the weapons, platforms, trained personnel, information, and supporting forces needed to accomplish military tasks. The ability of commanders to collect and process information, and to use that information to command and control their forces, is at the center of operational concepts. Concepts development should begin by identifying the knowledge needed by the warfighter, how it will be gained, and where it will be disseminated.

To illustrate the use of this taxonomy, consider the operational task of neutralizing TBMs. In order to neutralize enemy TBMs, it may be necessary to build a unique system to identify their use (by their launch signature, for example) and location. Additionally, perhaps the operational concept constructed around these purpose-built systems could be optimized with the use of other specialized systems (communications links, for example). The Air Force investment focus, however, should remain on the operational task of neutralizing ballistic missiles, rather than on whatever systems the Air Force selects to provide indications and warning. Why? Because it is possible that new, more effective or more efficient technologies will emerge from the commercial world or Government laboratories. These technologies should be incorporated to improve or replace the original concept.

From another standpoint, information may be available from other DoD or national systems that, if properly integrated and disseminated, could augment or enable performance of this task. Some argue that current space systems have been developed and purchased to deliver a particular type of data that is not easily integrated with data from other systems or with warfighting forces. Missile warning, imagery, and other remote-sensing systems serve as examples of systems that provide vital strategic data to the NCA, but in a stovepiped fashion. To help warfighters accomplish specific operational tasks, however, data from these systems must be fused together to provide the knowledge needed. Concept proposals need to be flexible enough to exploit these additional resources.

Furthermore, a new sensor may be needed to provide the identification and targeting capability desired, but present supporting capabilities might be sufficient if commercial systems were included in the mix. Focusing on the task rather than on a specific concept would allow planners to eliminate unnecessary specialized support systems from consideration. Focusing on acquiring the knowledge needed to accomplish specific operational tasks should allow the Air Force to determine which pieces of the concept it needs to develop, and which can come from commercial services.

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[2] The "enterprise, effectiveness, and efficiency" framework has been adopted from work by Carl Builder of RAND.

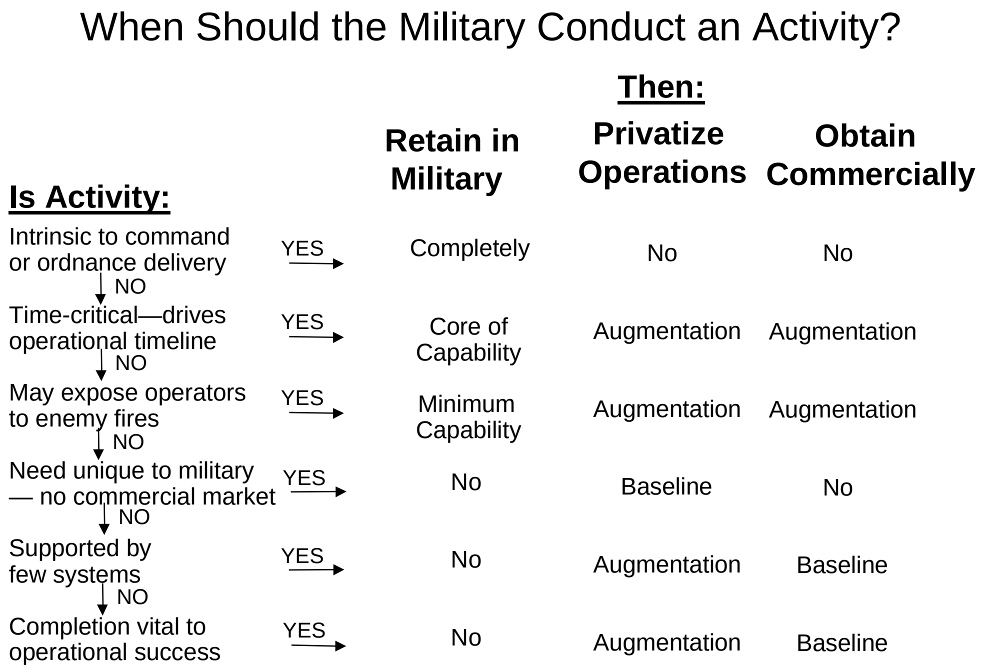
> The Air Force should minimize the supporting infrastructure it provides organically, acting as “steward” whenever possible and as “leader” only when necessary.

What do we mean by “leader”? What do we mean by “steward”? The Air Force acts as a “leader” when it performs internally all of the steps in providing a capability, including innovation, operation, and employment. As a “steward,” the Air Force may oversee the innovation and operation performed by someone else—private industry, for instance; the only internal operation might be the actual employment of a capability.

5.2 Military Considerations for Determining When the Military Should Conduct Activities

But when must a function such as communications be performed by the military? When can the function be “privatized” (here defined as being provided by a commercial entity, under the general oversight and responsibility of a military organization)? When can the function be bought on the open market from commercial sources? An important consideration for these decisions is the following rule of thumb: A function is military in nature when it has a near-term or immediate effect on lives or the safety of equipment in accomplishing a military mission.

The following framework may be useful to consider important aspects of functions performed by or for the military to help determine whether they are core military functions, could be privatized, or could be services obtained commercially:



When Should the Military Conduct an Activity?

Is Activity:		Then: Retain in Military	Privatize Operations	Obtain Commercially
Intrinsic to command or ordnance delivery	YES →	Completely	No	No
↓ NO				
Time-critical—drives operational timeline	YES →	Core of Capability	Augmentation	Augmentation
↓ NO				
May expose operators to enemy fires	YES →	Minimum Capability	Augmentation	Augmentation
↓ NO				
Need unique to military — no commercial market	YES →	No	Baseline	No
↓ NO				
Supported by few systems	YES →	No	Augmentation	Baseline
↓ NO				
Completion vital to operational success	YES →	No	Augmentation	Baseline

Figure F-21. *Military Considerations for Making Decisions Concerning Military Activities*

In certain cases where an activity does not follow the framework, it might still be desirable to maintain some minimum military capability. For instance, when an activity can be supported by only a few systems, then the military might want to retain some core of people and equipment in order to have some measure of ownership or control. In this case, the activity is a candidate for privatization. Commercial entities can perform the activity in some cases even when successful performance is vital to the completion of a military task—so long as time is not an issue.

Consider the example of wideband communications (see Figure F-22). The Air Force currently provides almost every portion of the communications "value chain" (that is, the management of the development, acquisition, and launch of satellites, the management of satellite buses, the purchasing of terminal equipment, and the management of local networks for Air Force users). The Air Force even provides significant numbers of people to DISA, which manages the bandwidth and provides the communications services from the satellite. How much of this supporting infrastructure should the Air Force provide? Should it be a "steward" or a "leader" in areas such as communications? The answer depends, in part, on the availability of that support from external sources, and in part on the strategy the Air Force wishes to follow in obtaining supporting infrastructure.

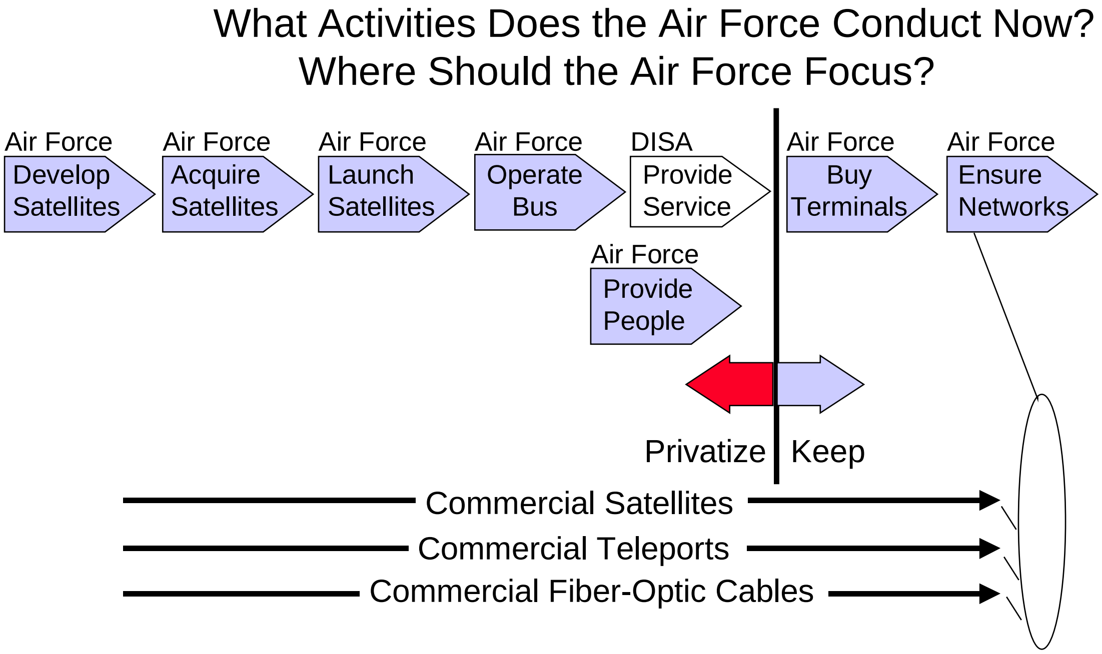
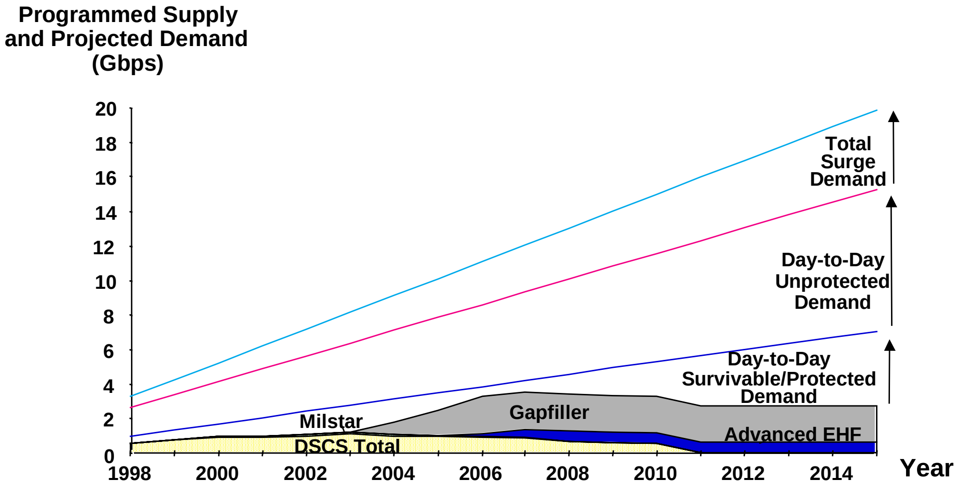


Figure F-22. *The Air Force Role in the Communications "Value Chain"*

In principle, the Air Force could privatize all of the functions up to the purchase and operation of ground terminals and the local military networks. In some cases, even these functions may be candidates for privatizing or obtaining commercially. What is vital, however, is that the Air Force shift its attention from providing individual systems to the much more important task of ensuring that the needed connectivity between military and commercial systems is achieved. Moreover, the Air Force needs to ensure that these systems provide the needed information flow among all elements of the information management architecture.

How much military communications is needed? The U.S. Space Command Capstone Requirements Document provides a projection upon which Figure F-23 was based.

What Are Projected Military Communications Needs? What Are Air Force Options?



Source: United States Space Command

Figure F-23. *Military Communication Needs in 2010*

As projected, the total amount of communications needed in 2010 for all military users will be approximately 15 gigabits per second (Gbps). Additionally, the aggregate data rate capacity of all military systems currently programmed and planned is expected to be approximately 4 Gbps. How can we close the gap? Recent attention has focused on how commercial systems may be used to carry military communications more cheaply than military-unique or -owned systems. The idea is that military-owned and -unique systems may be used where the special capabilities they bring (for example, survivability and jam resistance) are most needed—for instance, within a contingency theater of operations.

The Air Force has developed communications satellite systems (Milstar, for instance), which ensure that some core military capacity will exist in the presence of high levels of radiation or jamming. The commercial world will not develop any similar capabilities in the foreseeable future. However, most of the capacity shown above is expected to come from wideband systems such as the Defense Satellite Communications System and Gapfiller. Commercial systems and services may provide this capacity with some minimum amount of protection to units in the theater and for units in permissive environments. In this way, the Air Force would save money that could be used to improve warfighting capabilities, rather than spend it on support functions.

An improved information management architecture should be the foundation for operational concepts that improve current capabilities and enable entirely new capabilities.

The information management architecture must enable the Air Force to adapt to changes in strategy and tactics with new operational concepts. For example, since the end of World War II, the United States has experienced a decline in its access to bases overseas. The end of the Cold War hastened this trend and brought with it a reduction in force size and forward presence. This changing strategic context has necessitated the development of new concepts for crisis response from bases on U.S. territory.

One example is the AEF. Deploying forces must have the ability to tap into the Global Grid at any point in their operations—from planning through deployment and combat operations until return to base. The information management architecture must support Expeditionary Air Forces by delivering information to them as they react to crises anywhere on the globe.

A second exemplar operational concept involves space. In the future, other nations will have access to large quantities of imagery, communications, and other products delivered from or through space. Furthermore, other nations may employ weapons through space, or put offensive systems into orbit. In order to defeat enemy threats seeking to exploit these capabilities and to conduct operations within the space environment, the Air Force will need the ability to build a "recognized space picture." This recognized picture must be capable of identifying threats, assessing enemy attacks, and guiding U.S. forces to appropriately respond. The recognized space picture needs to be one of the core pieces of the information management architecture.

5.3 Characteristics and Attributes of Effective Future Information Architectures

> The information management architecture must allow customized C^2 concepts for each unique commander and mission.

The Air Force needs an information management architecture that allows it to realize the full potential of aerospace power capabilities. For instance, it should enable en route targeting and mission planning for deploying AEFs and allow operations to be conducted at austere sites. These forces may be sent rapidly anywhere in the world, so the information architecture needs to enable seamless global connectivity. In addition, the architecture will need diverse routing across multiple commercial and military communications systems and networks to provide assured information delivery. The architecture must be

- Mission-centric
- Developed from capable components
- "Custom tailorable" by each commander
- Adaptable to new situations
- The enabler for the commander's C^2 concept

An improved information management architecture is one that allows joint military forces to accomplish tasks more *effectively*. Here, the emphasis is on improving the outcome of an important mission or task, or accomplishing that mission or task in a more desirable way. Information management includes all aspects of collection, processing, exploitation, and dissemination. In addition, information management includes those capabilities a commander needs to exercise command and control. We do not suppose that the Air Force needs to provide all the systems or to control the operations necessary to conduct these functions. An improved information management architecture, though, will need to operate within and contribute to these functions; hence the functions must be explicitly treated in the design. *The architecture must integrate information from global and theater assets, both inside and outside the Air Force, and enable seamless C^2 of forces around the globe.*

The complexity of the future joint and combined forces structure will demand new approaches to manage the interfaces across systems and architectures. The Air Force should identify a single entity responsible for putting these interfaces together within the information management architecture and for ensuring that advances in the commercial world are exploited. The ability to task out-of-theater information collection assets, fuse this information with that from theater-based assets, and integrate this with information provided by other agencies is vital.

5.4 Military Strengths From Robust Information Management

Improved information management might allow Air Force and joint military forces to accomplish their tasks more *efficiently*, thereby reducing the resources needed for these tasks. The information management architecture must exploit commercial technologies in order to be current and affordable.

To be viable in the long term, the information management architecture must be able to adapt to an uncertain future. Military budgets may continue to decline. At the same time, the growth of commercial capabilities may obviate the military's continuation of all the functions it now performs, and may make some current operational concepts obsolete. On the other hand, new technologies may offer potential adversaries dramatic improvements in specific capabilities. The Air Force needs to exploit the phenomenal technological growth in commercial industry in order to enhance Air Force capabilities, decrease costs, and hedge against technological surprise. *The Air Force should use a diverse set of providers for supporting operations in order to obtain the greatest capabilities, robustness, and cost benefits.* The Air Force needs to learn how to employ commercial systems and operations in a way that does not lead to unintended consequences for military operations or national security. The growing complexity and interdependency in civilian infrastructures might unintentionally introduce vulnerabilities into military operations. Adversaries might be tempted to identify and exploit perceived weaknesses. The Air Force must be careful not to let reliance on commercial operations make it vulnerable to single-point failures. The effect of attacks on key infrastructure nodes must be mitigated by proliferation of these nodes and alternative pathways. In addition, the Air Force must not be held captive by a single commercial provider or become completely reliant on commercial providers in order to conduct time-critical operations.

The Air Force needs to develop a strategy to make investments in commercial systems and operations. That strategy must increase needed capabilities, make these capabilities more robust against failures or enemy action, and decrease costs. The investment strategy must be adaptive to actual events and not dependent on predicting military demand, commercial supply, or technological innovations. Capabilities from other DoD components or U.S. Government agencies also may be useful to the Air Force. When they are used, however, the relationship should be viewed as *ad hoc*, not an entitlement for the providing agency to receive Air Force funding indefinitely in exchange for provision of the service.

One may look at some of the space capabilities that the Air Force provides and determine the degree to which the military need is unique and how important the specific systems are to that capability. Figure F-24[3] shows the result.

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[3] Adapted from Kenneth V. Saunders et al., "Priority Setting and Strategic Sourcing in the Naval Research, Development, and Technology Infrastructure," MR-588-NAVY/OSD, Santa Monica, CA: RAND, 1995.

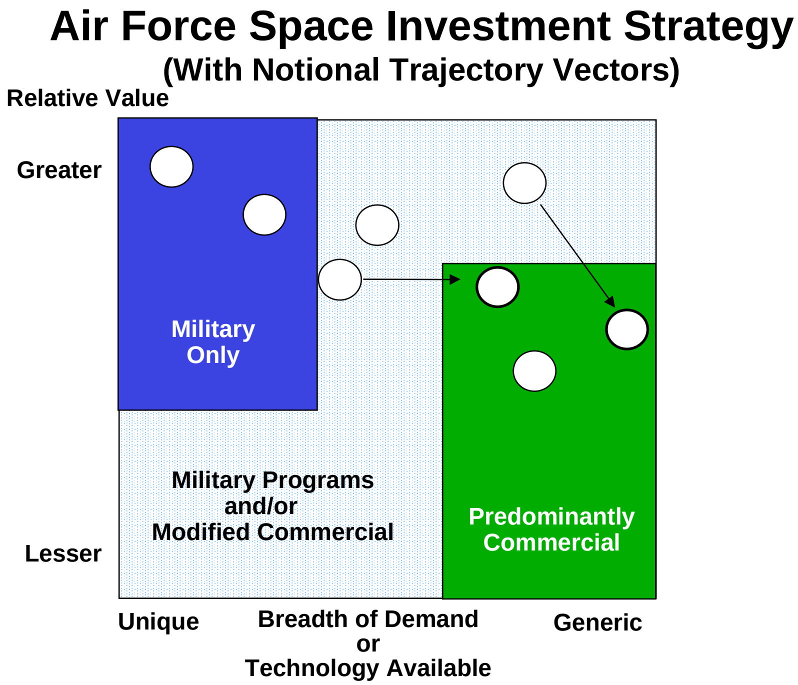

Figure F-24. *Air Force–Provided Space Capabilities*

Across the bottom of Figure F-24, the breadth of demand ranges from military-unique to general. The more general the demand, the greater the quantity we expect to be available from industry. Along the vertical axis, the relative value of an additional system to a military capability ranges from low to high. A low score does not mean the capability itself is unimportant, nor that the systems are not capable. Rather, it implies that the relative value of an additional unit is not high and hence should not be an area of focus for military investment.

We should note that the position of systems within this space may change over time. For example, it may have been that at one time military communications could be satisfied only with military systems. Since then, however, the commercial communications industry has invested in capacity, making demand more general. In addition, we may have found that the relative value of an additional military communications satellite began to fall off after some level of owned capacity had been reached. This does not mean that existing systems have decreased in value, but that additional systems would provide diminishing returns to scale. We have notionally placed exemplar systems on this graph to indicate where they may fit within this trade space.

Three general areas can be constructed on this diagram. The upper left-hand corner reflects an area where the relative value of the next system to be built is high but the technologies and demand are so specialized that the commercial world is unlikely to provide them. Conversely, the lower right-hand corner represents an area where the relative value of the next military system is low but the technologies are generic and in demand commercially. In between is an area that may be satisfied either with "commercial-like" military systems or with commercial systems that have been purchased for military use. This may be either because the activity is too vital to outsource completely (as in the upper right-hand corner) or because the military value is both relatively low and unique to the military (as in the lower left-hand corner).

As a notional example of present communications systems, we have constructed Figure F-25.

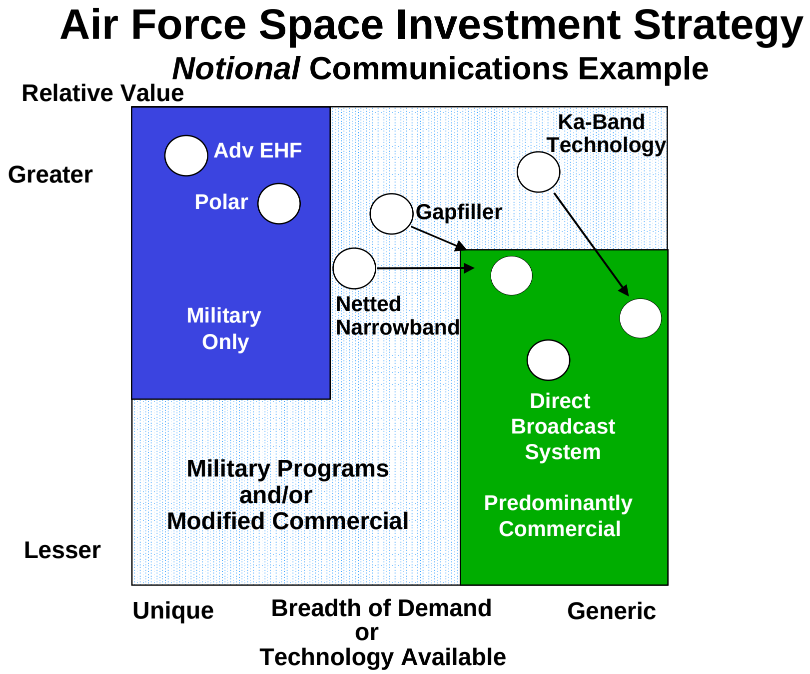

Figure F-25. *Present Communication Systems*

Here, we see that certain systems such as Advanced Extremely High Frequency (EHF) and polar communications are military-unique (the commercial world is unlikely to supply them in the quantity or quality needed by the military). In addition, the units to be provided have a high relative value; each added unit provides something necessary and unique. On the lower right-hand side we see systems such as Direct Broadcast Service and wideband systems, which the commercial world has provided in large measure. In between, we might have systems such as Gapfiller, netted narrowband systems, and Ka-band systems that utilize many elements from the commercial world but are either too important or too specific to the military for the commercial world to provide. It is possible that technological developments might push these systems into the lower-right hand corner. On the other hand, some unexpected political development may increase the relative value high enough to incline the military to own these systems.

5.5 Conclusions

The information management architecture must enable efficient Air Force employment of

- ISR, communications, launch, navigation, and force application assets
- National security organizations', civil agencies', and commercial industry's systems and architectures
- Robust and serviceable networks, not vulnerable to attack on a single node or relatively few nodes

… in order to enable

- A customized C^2 concept for each commander and situation
- Warfighting concepts with entirely new capabilities

- Improved mission outcome with current forces
- Robust operations not vulnerable to single- or few-point failures

There are three fundamental ways in which a better architecture may help; in order of importance:

- By helping redefine the Air Force enterprise—that is, enlarging or improving the contribution of the Air Force to military operations and capabilities
- By improving the effectiveness of operations—for example, improving their speed, precision, or lethality, or reducing the risks to U.S. forces
- By enhancing the efficiency of operations—that is, making it easier to conduct operations and cheaper to obtain the necessary systems

6.0 Technology Enablers

6.1 Introduction

It is necessary for the Air Force to play an active leadership role to assure access to the technology enablers required in realizing the vision of Battlespace Information Dominance. The Air Force is well equipped to provide this leadership, which will include setting new standards for proactivity, innovation, and vision.

Realizing the vision of Battlespace Information Dominance will require treating the supporting information infrastructure as a top-level, networked system. The resulting infrastructure will be a hybrid system utilizing space and surface components as well as Government and commercial elements. Substantial exploitation of the capabilities of a variety of space-based functions, including telecommunications, remote sensing, and navigation, will be required. It will be necessary to leverage the explosion of leading-edge commercial space systems, technology, and practices, as well as defining core, military-unique capabilities. It is essential that the resulting information dominance capability manifest the attributes of timeliness, accuracy, robustness, reliability, and affordability.

The scope of this challenge requires that a complete systems approach be used to define and realize the enabling capabilities. This approach must include an appropriate combination of technology development, collaborative endeavors, and partnering. In addition to securing hardware and software capabilities, the scope of necessary enabling activities will include assuring seamless, transparent interoperability and also appropriate access to radio-frequency spectrum. These enabling activities will define and tailor the evolving Global Information Infrastructure (GII) and the Defense Global Grid (DGG). The wide variety of technologies and related processes and activities required to realize this vision are presented in this section.

Enabling technology drivers with a focus on information technology are discussed in the following paragraphs. The thrust of this section, however, is largely to establish the top-level technology perspective rather than to provide a listing of key technologies. It is more important to first understand the context and define strategic imperatives; having achieved that, the definition of specific, focused enabling technology investments can follow. Furthermore, the SAB Ad Hoc Study on Information Management to Support to Warrior, conducted in parallel with this study, expands on these concepts and defines the nature and functioning of the Battlespace InfoSphere.

6.2 Attributes of Future Air Force Information Management

Previous discussion of the Global Grid focused on the transport of *data* throughout the grid. This section significantly extends that concept by addressing not data, but *information*—its generation, filtering, aggregation, fusion, and dissemination. The connectivity, bandwidth, and assurance issues discussed to this point, though critical, cannot achieve the full potential of an information-dominant C^2 system if the information products that are produced for users of the system are done so independent of one another and without regard to the capabilities and monitored performance of the grid over which they are disseminated.

The limitations and deficiencies of our legacy stovepipe information systems have necessitated our migration toward federated information systems that are capable of passing information from system to system. Such system architectures must permit one system to exploit data and/or information that is processed or produced by another. Though near-term federated systems will be interconnected and capable of limited communication between each other, systems in total—legacy and future systems alike—do not, nor are they planned to, act, interact, and react within the context of one another.

As technology proliferates around the globe, non-friendly actors will have ready access to capabilities which until only recently were available to a select few. Our challenge in today's information age is to ensure that our commanders are armed with the tools to guarantee they can operate within the decision cycle of any potential adversary. War theory has demonstrated that the commander who executes the shortest decision cycle has a significant advantage on the battlefield. Timely, accurate, relevant *information*—not data—is the ammunition required to make the right decisions. Bombarding our decision makers with an inordinate amount of data is not a synonymous solution. Data must be "trimmed" down to the least common denominators; that is, the *information* that is hidden within the data is the key to understanding.

Having factored the data into constituent parcels of information, however, is of little, if any, value if the information arrives too late. Information dissemination plays an equally important role in properly arming our decision makers. In this regard, a 70 percent solution, for example, is infinitely more apropos than a solution that is 100 percent correct but too late to execute. For this reason and others, tomorrow's Air Force information systems must continue to evolve into an integrated, closely coupled yet widely distributed system of systems with a common information management architecture. Tomorrow's information systems must operate as an omniscient, fault-tolerant organism, capable of prioritizing and optimally fulfilling its requests while reacting to a constantly changing environment. Such a system of systems is envisioned to be built upon a Common Information Infrastructure (CII), consisting of a COE utilizing a Common Data Environment that communicates through a Common Communications Environment. With the CII as the overarching architecture, a massively interconnected system of systems emerges as the realization of a C^2 system that, theoretically, is capable of directing near-instantaneous firepower to any target on the globe or beyond.

Throughout a number of recent DoD, Air Force, and other Service long-range studies, three characteristics consistently emerge as necessary features of an information-dominant C^2 system. Such a system must provide *global situational awareness*, *dynamic planning and execution*, and *seamless, transparent information exchange.*

As the Air Force transitions to an eAF with fewer troops in harm's way, our C^2 systems are challenged to provide accurate, consistent situational awareness to remote rearward locations. Global situational awareness permits the generation of an on-demand, comprehensive operating picture of the battlespace, providing a rendition consistent with all other representations of that same battlespace by other decision makers. Hence, the term *common operating picture.* Knowledge of red/blue/gray air, space, surface, and information activities would be represented in the COP, giving echelons of decision makers the information edge they require to successfully execute military operations in their areas of operational responsibility. Global situational awareness implies the ability to "out-know" your adversary. The key to attaining global situational awareness is sufficient information in time to accomplish militarily significant objectives.

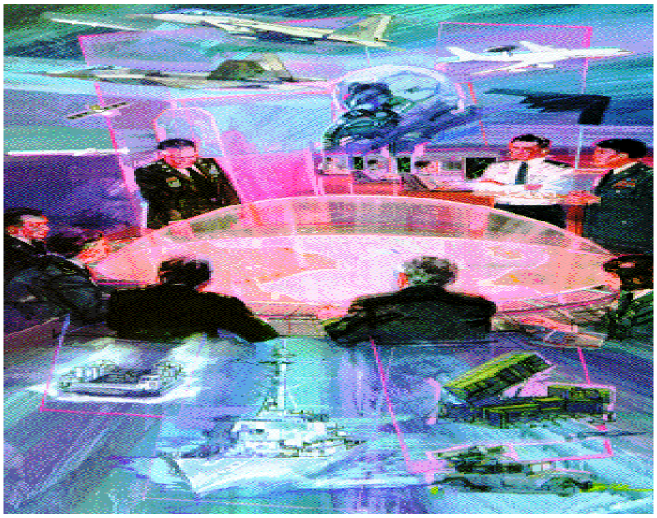

Figure F-26. *Future Decision Making*

Three elements are critical to achieving a state of global awareness: precision information, consistent battlespace knowledge, and a global information base. Precision information addresses tenets of not only accuracy, but also timeliness. Precision may be a progressive function of time. The COP would reflect any uncertainties corresponding to information depicted. A revolutionary advantage of a system-of-systems approach to C^2 is the precision attainable through the fusion of previously stovepiped data. Consistent battlespace knowledge refers to the trusted coherency among the information presented in the COP from various, distributed sites, as well as that between the mapping of the rendered information and the real world. Consistent battlespace knowledge requires the cognitive exploitation of a dynamic suite of multiple sensors and information sources to derive status as well as to predict intent. The global information base may be thought of as a virtual and massively distributed, logically integrated repository of qualified, static, and dynamic information that had been or is processed from multimedia data types. It is a self-organizing, self-optimizing architecture that bridges and unifies all levels of situational information.

To effectively control the vast resources of a complex military campaign requires that all participants know the present plans and their roles in those plans.[4] Campaign planning is a simultaneously iterative process of representing the COP to detect and assess threatening situations, determine appropriate courses of action (COAs), construct a plan to execute the COAs, prosecute the plan, reassess the situation, and update the COP. The objective of dynamic planning and execution is to provide our decision makers with the real-time ability to shape and control the pace and phasing of engagements. Critical attributes of a dynamic planning and execution process require that it be predictive, integrate force management and execution, and be capable of real-time sensor-to-shooter-to-sensor operations.

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[4] Air Force Scientific Advisory Board, *Vision of Aerospace Command and Control for the 21st Century*, SAB-TR-96-02, Oct. 1996, pp. 3-11.

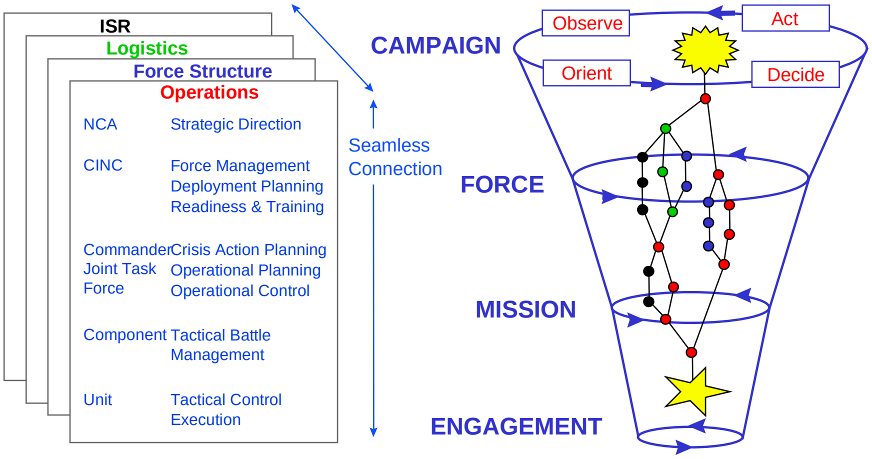

Figure F-27. *Dynamic Planning*

As implied in the figure above, combat operations, force structure, logistics, and ISR planning processes are functionally similar, and all are critical to preparing and executing a campaign plan. Dynamic planning and execution, therefore, must consider the relationships between and within each process for our own as well as non-friendly forces to arrive at COAs that maximize mission effectiveness while minimizing risks and costs. Interoperability and compatibility among the array of systems that make up each of our planning systems is insufficient to achieve the optimal solution sets that a future commander requires. Component systems must not only exhibit compatibility between each other, they must transfer knowledge to and from each other to expedite more relevant, executable solution sets to evolving crises.

Predictive planning is that element of dynamic planning and execution that ingests relevant observations and information, reasons logic from that information, and predicts most likely scenarios that one can expect as a consequence of the observed occurrences. Predictive planning emphasizes machine-learning techniques but exploits the experiences of its users and subject matter experts to correctly bias its prediction. Consistent with eAF deployments, predictive planning is envisioned to rely on geographically dispersed individuals and teams. Consequently, there exists the requirement for shared, real-time, distributed collaborative planning integrated within the system-of-systems information management architecture.

Figure F-28. *Predictive Planning*

The ultimate C^2 system would conduct sensor-to-shooter-to-sensor operations nearly instantaneously, condensing the observe-orient-decide-act loop execution time to zero. It is a moot point whether or not such a system can ever be realized. The goal, however, is for boresighting our direction. We must be committed to aggressively progressing toward this goal to achieve the realistic goal of *in-time* sensor-to-shooter-to-sensor operations. A C^2 system of systems possesses an underlying seamless, transparent capability to provide information services anywhere, anytime, for any mission. Inherent in this capability is the concept of universal information accessibility across heterogeneous transmission media, each with unique characteristics. Critical elements are a distributed information infrastructure, universal transaction services, assurance of services, and global connectivity to or through the surface, air, and space. The distributed infrastructure provides physical through transport layer connectivity among military, Government, and commercial systems and networks, but also extends into presentation and application layers to populate and link entries in a global information base. Universal transaction services are available to automatically translate, mediate, and condition information as required. Guaranteed, uncorrupted information delivery is one assured service. Others are detection and protection from information warfare operations, and fault-tolerant and information-adaptive delivery mechanisms to ensure that information is routed in the best manner possible, where performance is guaranteed dependent not only upon the state of the communications grid, but upon the utility and criticality of the information in the integrated C^2 process.

The Air Force cannot possess a seamless, transparent information exchange capability if it is not globally connected to all its aerospace forces and platforms. The mix of assets by which this global connectivity is achieved is not within the present scope of this discussion. An appreciation for the challenges, however, is warranted. The Air Force consists of users and platforms that may be terrestrially fixed or mobile; may be in space or air, agile or mobile; may have over-the-horizon or line-of-sight requirements; may require antijam and low probability of intercept; and may be severely bandwidth constrained. The diversity of considerations is broad. Yet a global connectivity architecture must be managed to address all considerations while simultaneously satisfying the need for information services anywhere, anytime, for any mission—*in time*.

6.3 Technology Challenges for Future Air Force Information Management

The elements *global situational awareness, dynamic planning and execution*, and *seamless-transparent information exchange*, taken together, will effect information-dominant, global C^2 of our aerospace forces. The objective of global situational awareness is to provide a comprehensive, integrated operating picture with any view consistent with any other. The goal sounds simple; the implementation is not.

Tailoring views from data that have been collected with different fidelities, latencies, and accuracies and from heterogeneous sources is certainly a challenging task. It has not been addressed from a global macro perspective. In the past, the tasks of sensor development, fielding, and employment were accomplished relatively independent of one another. Redundancy compensated for lack of interoperability. Recent fiscal constraints, reduced personnel levels, and recognition of the benefits of joint planning and execution dictate an end to the inefficiencies of redundancy. “Do more with less” is an implicit requirement. The challenges we confront in information management and the demands that are imposed upon our C^2 architectures have never been greater.

The Air Force Research Laboratory (AFRL) must continue to improve its focus on discovering, developing, and transitioning more efficient methods of extracting, processing, exploiting, and disseminating relevant information to and for information consumers securely. Information extraction processes must address both real-time and archived data and information sources. Metadata generation and management, to include such attributes as pedigree, space, and time, become as important to the information retrieval and extraction process as the data or information itself. Knowledge of collector location and capabilities is important to achieving efficient utilization of real-time data sources in future infosphere architecture. The architecture must support the closely coupled integration and operation of collection, processing, exploitation, and dissemination processes. Significant synergies can then be forecast while stovepipe philosophies associated with our current systems and processes give way to mission-centric philosophies that rely on multiplatform, multisensor exploitation. National and tactical assets must come together, supported by doctrine and policy that recognize the criticality of achieving these synergies.

Powerful fusion engines that are knowledgeable of all the data characteristics, limitations, and advantages of employed heterogeneous data sources will be required to present an optimal interpretation of unfolding events. The advancement and transition of cognitive sciences to these information processing fusion engines is critical. Fusion engines will be required to reason; they must be able to learn, extrapolating responses based upon historical event patterns and cause-and-effect relationships. Their algorithms must dynamically respond to different circumstances having different input parameters. They must be able to work in a real-time space-time-accuracy trade-space.

An inference exists that optimal execution of the trade-space requires knowledge not only of the needs of the particular information consumers, but also of the status of the grid over which the information is disseminated. Information generation and process control services must interact with grid performance monitoring services to assure product delivery. Users should be profiled and their demands analyzed by an “intelligent push” mechanism that attempts to preempt users with information that they require based upon the current situation relative to past requests and actions. Seamless multilevel security is required throughout the entire architecture,. The challenge is to integrate multilevel security such that it does not inhibit the distribution of information to users who require it, while concurrently preventing distribution to those who do not have a need to know or are not authorized its receipt.

Several recent “visionary” studies have been independently completed by the Chairman of the Joint Chiefs, the Air Force Scientific Advisory Board, and Air University. Several recurring themes with regard to ISR are evident throughout these studies and are supported by the concepts that have been identified by this panel. They include[5]

- Sensors that can detect a wide variety of emissions and signatures day or night and in all weather
- Use of advanced expert systems and automated decision aids to support analysts and decision makers
- Near–real time fusion of multisensor data
- Worldwide communications for every level of warfighter and decision maker

The long-term components for the Grid Services and Battlespace Awareness layers of *The Advanced Battlespace Information System* roadmap for *Joint Vision 2010*, published by the Joint Chiefs of Staff (JCS) and the office of the DDR&E, are particularly applicable to and strongly endorsed by this panel. These components are listed in the following table.

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[5] Lt Col David Honey, *Intelligence, Surveillance, and Reconnaissance Development Plan*, ESC-TR-97-041, Electronic Systems Center, Air Force Materiel Command Deputy for Development Plans and Advanced Programs, Hanscom AFB, MA, 5 March 1997.

Table F-5. *Operational Layers and Components*

Operational Layer	*Component*
Grid Services	Distributed Access to Consistent Information
	Heterogeneous Information Retrieval & Integration
	Grid Predictive Management
	Grid Integrated Defense & Management
Battlespace Awareness	Knowledge-Based Information Presentation
	Warfighter Cognitive Mission Support
	Warfighter End-to-End Task-Synchronized Mission Support Products

6.4 Enabling Commercial Space Capabilities

It is essential that the Air Force take advantage of the unprecedented development of commercial space-based capabilities for communications, remote sensing, and navigation. This explosion of capability is well known, is predominantly led by U.S. companies, and provides attractive, cost-effective options for the Air Force for non-core military missions. While it will continue to be necessary for the Government to maintain critical space-based systems and capabilities for essential, unique functions, increased use of commercial systems and services can provide capability, robustness, reliability, reach, and cost-effectiveness unimagined only a few years ago. It is also clear that, in the current era of constrained budgets, such use of commercial systems and services will enable the Air Force to focus its technology investments on the most highly leveraged, mission-critical requirements.

It is necessary that the Air Force take full advantage of the concept of “use of commercial assets.” This is a far broader concept than merely buying commercial hardware and software components and systems to substitute for a current Government capability. In addition to the enlarged range of commercially provided functions suggested above, leverage and cost-effectiveness can be realized by also employing commercial procurement and management practices, processes, standards, and procedures whenever possible.

The full potential of the vision of Battlespace Information Dominance can be realized only by assuring seamless interoperability among the various elements of the space- and surface-based information infrastructure. This in turn requires that the Air Force increase its understanding and involvement with at least four activities related to the enabling commercial space capabilities. The first of these activities is to maintain an intimate familiarity with the emerging commercial systems and capabilities. Second, it will also be necessary for the Air Force to become involved with the development of standards and protocols that are essential to enable interoperability among the systems and the surface infrastructure. Third, the Air Force must take a leadership role in the processes to secure assured access to the radio frequency spectrum required by commercial and Government systems around the globe. Lastly, it is essential for the Air Force to maintain cognizance of potential adversaries’ access to and use of evolving U.S. and international commercial space capabilities.

This discussion would be incomplete without emphasizing that one of the most highly leveraged enabling commercial space capabilities is access to space. Studies over the past year have concluded that almost 2,000 satellites will be launched worldwide within the next 10 years. Approximately three-quarters of these satellites will be commercial, and most of them will be communications satellites. The cost and availability of launch continue to be a significant portion of the cost of all space systems.

As the Air Force increasingly uses commercial space-based capabilities, it is in the Air Force’s interest to assure an adequate, cost-effective launch capability. It is therefore appropriate for the Air Force to take a leadership position to assure that the current U.S. investments in launch vehicles will result in systems that are attractive for launch of commercial satellites. It is well known that the current U.S. launch vehicle developments are characterized as being commercial ventures because industry is making significant investments in these programs with Government partners. These developments are focused, however, on Government launches rather than on the much more frequent commercial launches. There is a significant difference between having a commercially developed launch capability and having a launch capability that is attractive to commercial launches. The Air Force should take steps to ensure that these current U.S. launch vehicle investments result in capabilities relevant to all launch customers, not just to Government launch customers. These new launch systems should be targeted to lead in significantly reducing all aspects of the cost of access to space. The availability, reliability, launch base procedures and processing time, lift capability, and booster-to-payload interfaces should also be made compatible with future commercial requirements. By so doing, the Air Force will contribute to greater cost-effectiveness for both Government-unique space systems and commercial space systems used to provide service for the Government. By assuring a world-class U.S. launch capability, the Air Force would also significantly contribute to continued U.S. competitiveness and leadership in space.

6.4.1 Use of Commercial Satellite Communications Services First

During the 1980s and 1990s, DoD continued to require satellite communications (SATCOM) with military characteristics such as survivability, global reach, and antijam capabilities. The evolving, robust global reach of commercial satellite services should encourage changes in this approach. The key enabler is that in addition to significant current commercial capabilities, U.S. commercial industry will provide over 500 Gbps in the Ka-band frequency range during the first 5 years of the next century. This capability will be provided by several U.S. commercial systems deployed in a variety of orbital regimes. By 2005, the military would therefore be able to communicate around the globe with multiple commercial SATCOM systems deployed in a diverse architecture. In addition to the revolutionary commercial SATCOM capacity and reach, there has been a mandated reduction in Air Force and DoD mission reach. The next century will see the Air Force (and DoD) supporting no more than two simultaneous major regional conflicts (MRCs). With this change in mission responsibilities, the support requirements within and outside MRCs will vary. Just as our airlift is designed to rely primarily on reliable/survivable DoD transport within an MRC and commercial carriers (747s, etc., with the Commercial Reserve Air Fleet) outside the MRC, so will our communications be based on a similar concept. Military-owned and -controlled satellites will provide the warfighting CINCs with robust and survivable communication within the MRC, and commercial satellite reach will support less-than-vital communications outside the MRC. This parallel leads to the conclusion that the thrust for military satellite communications (MILSATCOM) should focus on supporting the warfighter within two MRCs, rather than on maintaining global reach. This shift in need will result in significant changes in the design of future military satellite constellations. Instead of global reach, MILSATCOM should be “transportable to an MRC.” Instead of maintaining a strategic focus, MILSATCOM should support the warfighting CINC. These changes in approach will alter the design criteria and result in focused core military support from satellite communications within MRCs, with basic and committed dependency on commercial terrestrial and satellite communications for the remainder of the globe. Based on current commercial deployment plans, the concept of a deployable MRC MILSATCOM system could begin the phased process to replace the current MILSATCOM programs around 2005. The first choice for the DoD would be to use commercial SATCOM services with specifically designed deployable MILSATCOM terminals for support to the warfighter within the MRCs. The deployable MRC MILSATCOM satellites would match the CINC’s requirements and be able to move to and support MRCs anywhere on earth. The future Global Grid based on Ka-band systems should have seamless interoperability between commercial SATCOM and MRC MILSATCOM. This concept could be based upon the new software-reprogrammable user terminals. The first choice for Air Force and DoD satellite communications should be over a commercial architecture with deployable MRC MILSATCOM available for the warfighter inside the two MRCs.

6.4.2 ServerSAT

In addition to use of "as-is" commercial SATCOM, a new concept called a ServerSAT, which would provide a high data rate gateway for inserting military traffic into the commercial SATCOM "cloud," has been developed. ServerSAT is described in Volume 1 of this study and in a Concept Definition paper submitted to the MILSATCOM Technology Planning Integrated Product Team at Space and Missile Systems Center Developmental Directorate.

FINDING AIM #4

Current acquisition and requirements processes are not designed to incorporate commercial capabilities across the Air Force mission areas.

RECOMMENDATION AIM #4a

AF/SC must ensure that the aerospace force robustly connects to the Defense Information Infrastructure and Global Grid and shapes the National Information Infrastructure and Global Information Infrastructure.

RECOMMENDATION AIM #4b

SAF/AQ should lead an effort to baseline the use of commercial systems for non-military-unique functions and implement them in a seamless, transparent, and interoperable manner.

Figure F-29. *DII, Global Grid, and Commercial*

Table F-6. *AIM Finding and Recommendation*

Finding AIM #10: Needs of 21st-century aerospace power for SATCOM will far outpace current procurement plans for DoD SATCOM architectures.

- **Recommendation AIM #10a:** Send all but critical traffic through commercial communications conduits. Move toward industrial funding, make bulk purchases through lead agencies, and move core communications through Milstar.
- **Recommendation AIM #10b:** Work with the Navy and ensure that the Air Force and DoD communications drive from DII to the NII to the GII and finally to the Global Grid. A robust Battlespace InfoSphere is critical to the future commander's success.
- **Recommendation AIM #10c:** The Air Force should take a leadership role to assure seamless, transparent interoperability between and among the various elements of national, military, civil, and commercial information infrastructure to assure proper utilization and leverage of space and terrestrial communications, remote sensing, navigation, and launch. (This will require a close working relationship with the commercial systems houses.)
- **Recommendation AIM #10d:** The Air Force should take a leadership role to assure an appropriate capability in information management. This is a broad topic including collection and archiving of related information, reliable and timely retrieval and dissemination, reliable and timely cross-indexing of information, reliable and timely transmission of time- (and mission-) critical information, and maintenance of systems and mission security.
- **Recommendation AIM #10e:** The Air Force (Assistant Sec for Space) should take a leadership role to enable joint planning and execution of mid- and long-range R&D among the various elements of the Government having an interest in space capabilities, development, or missions (USAF, USN, USA, USMC, NRO, NASA, BMDO, DARPA, etc.). It is absolutely essential to have as a partner the commercial industrial base in this planning process.
- **Recommendation AIM #10f:** The Air Force/DoD approach toward commercial space assets must be matured to account for the revolution in progress in space constellations, commercial space imaging, and commercial launches.
- **Recommendation AIM #10g:** Develop information security procedures and policies that protect sensitive aspects of commercial space activity (that is, vulnerabilities, operational concepts for military operations). Task Air Force Space Command to develop and implement operational plans and concepts that account for commercial space assets used for military purposes at the different levels of conflict.

6.5 Enabling Collaborative Technology Development

Significant leadership will be required of the AFRL to achieve the vision of information dominance for the battlespace. AFRL must develop new strategies to maintain the technical leadership essential to achieving information dominance. These strategies must incorporate appropriately defined collaborative activities and will be required because of a variety of fundamental changes that have been developing over the past several years. These changes include evolving battle doctrine, decreasing resource availability, emerging threats, and increasing capabilities available from the commercial sector.

The post–Cold War environment is characterized by reduced R&D budgets in the United States while relevant foreign technology capabilities are developing rapidly. Also, ready access to valuable strategic and tactical information by potential adversaries has become a reality. Dramatic advances in commercial space capabilities based in large measure on earlier Government technology investments also characterize this period. Combining these changes with the focus and relevance of Air Force activities to assure access to the enabling technologies is a worthy challenge for AFRL. Significant leverage can be gained by expanding the collaborative space R&D efforts recently undertaken by AFRL. AFRL has the lead for joint, collaborative planning and execution of mid- and long-range R&D among various elements of the Government having an interest in space, including the Navy, the Army, the Marines, the NRO, NASA, the Ballistic Missile Defense Organization, DDR&E, and Defense Advanced Research Projects Agency.

This effort is called the Space Technology Alliance (STA), and AFRL is to be commended for this excellent example of visionary, highly leveraged leadership. To realize the full potential of this collaborative approach, however, it is also essential for STA to follow through on its stated objective of engaging industry in a meaningful manner.

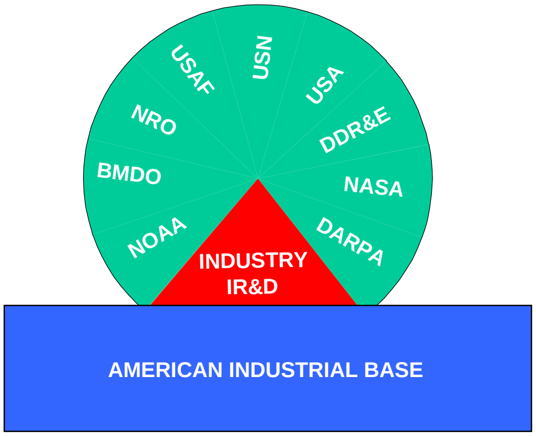
There are two distinct areas in which industry can add significant value to the STA process. These contributions can be characterized as being at the strategic level and at the technology level. Both of these industry contributions would enhance the up-front, planning aspect of STA. The first way in which industry can assist is to participate in occasional top-level meetings between senior executives from industry and their policy-making Government counterparts from the STA participants. The purpose of these interchanges would be for both sides to share their visions of future capabilities and requirements—that is, for parties on both sides to have an informed, relevant understanding of top-level, strategic thrusts for both Government needs and industry capabilities. This synergy at the strategic level would result in more focused, streamlined planning and execution for all space systems of interest to the Government.

The second way in which industry could assist would be to participate in meaningful, detailed, periodic technical exchanges between experts in industry and their counterparts in Government. These interchanges would promote synergy between technology advances planned by industry and those needed by the Government. Unneeded duplication of investment could be minimized, and benefits of earlier development results would be useful in planning future investments. These technical interchanges should also include reviews of ongoing technology developments with the goal being for Government managers to benefit from meaningful, in-depth reviews by a wider portion of the scientific community than is currently practiced.

It is understood that there are certain legal and bureaucratic conditions that must and should be satisfied prior to beginning this enhanced interchange between Government and industry. Clearly, qualified personnel within the Government must participate in properly structuring these interchanges to assure fairness and legal compliance. Also, industry participants will choose to reveal only nonproprietary matters in general meetings when competitors are present. In-depth interchanges between individual companies and the Government in which company plans, capabilities, and other proprietary matters are shared could continue as currently practiced on a case-by-case basis. It seems clear that the potential benefits are sufficiently significant that the Government should quickly define appropriate ground rules and begin this interchange process. Use of industry associations and/or existing advisory functions such as the Air Force Scientific Advisory Board (SAB) should be considered when the interchange process is defined.

FINDING AIM #2

Air Force Research Laboratory (AFRL) restructuring of the Air Force science and technology (S&T) efforts to support the drive toward "air and space" is timely!



RECOMMENDATION AIM #2

AFRL should develop a partnership that enables joint planning and execution of mid- and long-range research and development (R&D) with other government organizations and the commercial industrial base.

Figure F-30. *Air and Space S&T*

There are five premises underlying AFRL's collaborative approach. The first is that many of the underlying technologies are common for the widely varying missions of the various agencies. The second is that collaborative planning eliminates duplication and enhances synergy resulting from exchange of information. Third, involving industry in a meaningful way early in the process adds focus to technology planning as described in the preceding paragraph. This is particularly significant due to increasing Government use of commercial systems and technology. Fourth, there is the leveraging effect resulting from industry independent research and development (IR&D) being more closely focused on the strategic thrusts of the Government. Finally, this collaborative process will lessen the impacts of declining R&D budgets by enhancing focus of technology investment in both Government and industry.

6.6 Enabling Regulatory Activities

It is necessary that the Air Force take a new, leadership role in assuring access to essential frequency spectrum. It is also necessary to take an active role in influencing standards and protocols to assure interoperability among systems (Government and commercial, space- and surface-based).

The need for the Air Force to take a greater role in these matters derives from three fundamental changes that have occurred during the past several years. The first is the dramatic increase in commercial demand for frequency spectrum for both space and terrestrial applications. The second is the operational necessity for interoperability. The third is the increasing reticence by other countries to grant frequency usage to U.S. interests, whether Government or commercial. The existing processes that control these two areas of activity are different and hence will require tailored participation by the Air Force.

It is worth noting that a vehicle for immediate, effective Air Force participation in these efforts with appropriate industry participants already exists. Approximately 3 years ago, the U.S. commercial satellite industry chose to use the processes and expertise of an industry association for standards and protocol work and for spectrum management. The association selected was the Telecommunications Industry Association (TIA). For several decades, TIA has been the leading U.S. organization generating standards and protocols for wireless systems. TIA's activities also include relevant spectrum management work; TIA has well-established working relationships with the Federal Communications Commission (FCC) and other appropriate U.S. agencies as well as with the International Telecommunications Union (ITU). TIA bylaws and practices make it easy and attractive for Government representatives to participate in these activities.

6.6.1 Frequency Spectrum Management

There is an urgent need for the Air Force to better support the organizations which represent Air Force and DoD interests in frequency spectrum management activities. This is necessary in order to assure adequate and timely access to the spectrum required for Air Force missions. Leadership in staking out frequency allocation issues for developing (and current) space systems should be exercised within the Air Force through the Air Force Frequency Management Agency.

The frequency management process is well established and is one in which the Government leads with active support and involvement from industry. The FCC is the lead agency for domestic frequency management matters. The Department of State represents the United States in international frequency management activities with the ITU. ITU findings and decisions regarding frequency allocations, orbital assignments, and associated regulations carry the force of international treaties. The Air Force is a member of the Interdepartment Radio Advisory Committee, which advises the National Telecommunication and Information Administration (NTIA). Under current law, the NTIA, on behalf of the Federal Government, and FCC, on behalf of the private sector, work frequency management and develop the U.S. position in international negotiations.

There are three factors that combine to make Air Force participation essential: dramatically increased demand for spectrum, increasing difficulty in securing access to spectrum in foreign countries, and the need for more efficient Government processes to accommodate the first two factors both domestically and internationally. There has been a dramatic, worldwide increase in demand for spectrum during the past several years by commercial space and terrestrial communications systems. This demand has led to intense competition for unallocated spectrum. There have also been substantial efforts to convert existing space allocations to terrestrial use as well as attempts to redefine military allocations for commercial applications. Competition among space systems employing varying orbital regimes has also led to suboptimal solutions that may limit the effectiveness of the affected systems. More vigorous Government participation is required to preclude inappropriate loss of spectrum necessary for Government missions.

Foreign governments are becoming less cooperative with U.S. interests in granting frequency use rights for both commercial and military space-based communications. This reticence is driven in part by the emerging technical capabilities of these countries to compete with the United States in supplying space communications systems and services for both commercial and military applications.

The third factor is that the government processes, both within the United States and internationally, were not established to accommodate the volume and complexity of the current spectrum management issues. As a result, there is a pressing need for the Government to establish a much more proactive process within the United States to resolve issues and to reconcile positions in a much more timely and technically insightful manner. It is also essential that the Government establish a more streamlined and effective process for defining consolidated U.S. positions in order to more effectively represent U.S. positions in the international activities of the ITU.

In 1999, the SAB is conducting a special study to examine these issues and develop recommendations for more effective Air Force participation in spectrum management.

Table F-7. *AIM Finding and Recommendation*

Finding AIM #11: The importance of assuring access to usable frequency spectrum around the globe has increased to a critical level. The nations of the world are becoming much less cooperative in allowing U.S. commercial or military access to frequency spectrum. Simultaneously, the demand for commercial access for regional and global use of spectrum is increasing dramatically, placing a premium on this limited natural resource.

Recommendation AIM #11: Provide Air Force leadership participation in the frequency management processes both domestically and internationally to assure essential frequency access.

6.6.2 Standards and Protocols

The key to achieving seamless interoperability among communications systems to provide the Air Force and the warfighter with essential, reliable, and affordable "anytime, anywhere" telecommunications is the definition and implementation of effective standards and protocols. It is essential that the Air Force take a leadership role in defining its telecommunications needs and in assuring that the standards and protocols implemented result in true seamless interoperability among the various systems making up the overall GII and DGG.

As in the case of frequency spectrum management, there is an established process by which these objectives can be accomplished. It is similarly true that the Air Force as the lead Government agency for assuring communications capability for the warfighter must take a proactive leadership position in order to assure that the needs of the rapidly evolving U.S. military missions will be achieved.

It is important to understand, however, that the standards process is an industry-led activity. There are two fundamental reasons that the standards process must remain industry-led. The first reason is that the key to practical, efficient, economical standards is that they must be developed by the providers of the equipment and systems—that is, those most familiar with what will work while being cost-effective to develop, manufacture, and maintain. The second fundamental reason is that ever-increasing portions of the Government communications infrastructure will be based on commercial systems, technology, and services. The only practical, cost-effective manner to achieve the interoperability among many commercial systems that is essential for military missions is for the system providers to define and implement standards and protocols that are consistent with their individual business plans. Early involvement with these commercial entities enables greater leverage for DoD and Air Force needs.

The Air Force must become involved in order to ensure that its interests are properly represented. One of these interests is to be cognizant of rapidly evolving commercial capabilities, systems, and services that will be enablers for Air Force missions. Another interest is to assure that interoperability is achieved for applications that may be of interest only to the Air Force. The industry-led standards bodies encourage and have provisions for active participation by interested Government agencies. There are both domestic and international components to the process. It is also valuable to note that the commercial firms that participate in the industry standards bodies will generally welcome Air Force participation in the standards processes. The commercial communications industry fully understands that supplying services to the Air Force will be a component part of their business base but only if their systems and services are compatible with Air Force requirements.

6.7 Conclusions and Recommendations

6.7.1 Conclusions

6.7.1.1

Many technology thrusts already under way are highly relevant to achieving information dominance. It is essential for the Air Force to become more fully cognizant of current and future technology thrusts both in the Government and in the commercial industry sector. This increased cognizance is essential for the Air Force to understand what is possible and practical as increased reliance is placed on commercial systems and services. This increased technical cognizance is also necessary in order for the Air Force to continue to be an informed customer.

6.7.1.2

It is necessary for the Air Force to extend the concept of “enabling technology” to be much broader than conventional hardware and software components and systems. Also included is the proper understanding and application of system-of-systems methodologies. Only through this “big picture” approach will it be possible to properly integrate military-unique systems and capabilities with more cost-effective commercial systems and services. This top-down approach is also necessary to understand the capabilities of potential adversaries resulting from their access to emerging commercial capabilities for space-based communications, remote sensing, and navigation. The system-of-systems approach is also essential to define strategies for achieving robustness of integrated systems through such techniques as effective redundancy through use of dissimilar elements and capabilities.

6.7.1.3

There are significant opportunities for the Air Force to more fully control its own destiny by becoming proactively involved in regulatory and standards activities.

6.7.1.4

There is a very significant opportunity for the Air Force to enhance the focus, relevance, and leverage of its R&D investments by increasing its leadership of the current multiagency STA. Continued work with other Government agencies will eliminate overlap, develop synergy, avoid investment oversights, leverage other agencies’ investments, and assure a proper balance among near-, intermediate-, and long-term investments. The multiagency visibility of a broader scope of technology investment activities will also result in more focus on earlier insertion of technology advances into programs and missions.

6.7.1.5

It is essential that the Air Force take the lead in actively engaging industry in the activities of the STA. This is an essential component of STA because of the dramatic increase in use of commercial systems and services by the Air Force. More fundamentally, meaningful, up-front participation by industry experts (at both the strategic and technical levels) to help define investments and to assist in critique of ongoing technology projects is essential. This involvement of industry, while taking care to observe appropriate legal requirements and to protect proprietary interests, will also leverage industry’s IR&D for those companies wishing to provide systems, services, and technology for the Air Force.

Table F-8. *AIM Recommendations*

Recommendation AIM #12a: Implement necessary efforts to acquire the key technology enablers described in Section 6.2.

Recommendation AIM #12b: Employ the system-of-systems approach and methodologies to assure robust and effective realization of Battlespace Information Dominance.

Recommendation AIM #12c: Enhance the current AFRL leadership thrust for collaborative, joint technology planning and execution as represented by STA.

Recommendation AIM #12d: Actively engage industry at both the strategic (or executive) and technical levels as an integral part of STA.

Recommendation AIM #12e: Enlarge AFRL's scope of "technology development" to include proper exploitation of active participation in regulatory and standards bodies.

Recommendation AIM #12f: Acquire the resources and technical skills necessary to begin active participation in regulatory and standards bodies.

7.0 Migration Strategy

7.1 Introduction

As advancements in communications and information technology proliferate throughout the world, it is clear that the Air Force of the 21st century must have real-time, global information management capabilities allowing it to turn inside the decision cycle (observe, orient, decide, and act loop) of an adversary. Further, an eAF with its small forward footprint and relying on reachback support will have extraordinary needs for global, timely, and interoperable information management systems connected via seamless, robust architectures.

Battlespace awareness and the capability to move vast quantities of information will be the linchpin behind rapidly employable air and space assets tasked to provide desired outcomes to the National Command Authority and theater CINCs. Technical and operational innovations from the government and commercial sectors to secure command, control, communications, and intelligence information as the backbone of future operations require the Air Force to adequately fund enabling technologies and integrate these new capabilities into the operational force structure.

7.2 Assumptions and Assessments

Fundamental to ensuring that an information-rich COP is synchronized with operations is a migration strategy to transition to a user-friendly, interconnected information architecture that integrates the space, air, cyber, and terrestrial picture, providing decision makers at all levels with synoptic battlespace information and knowledge.

Assumptions:

- Desert Storm showed that current C^2 capabilities were inadequate to support over-the-horizon, deep target, and highly information-dependent, dynamic planning tools—that is, in-flight mission planning and Air Tasking Orders.
- The Aerospace C^{2}ISR Center (AC^{2}ISRC) was established in 1996 (as the Air and Space C^2 Agency) to provide a focal point for unifying and harmonizing disparate aerospace information management/C^2 needs and resources.

- Future engagements will force aerospace forces to communicate quickly with other Services and coalition partners through an architecture of interconnected C^2 that allows the Air Force to maintain its asynchronous advantage over an adversary.

- Robust information management must be suitably managed to ensure that data are transformed into information and subsequently into knowledge. A knowledge-rich warrior must not only be able to access a vast array of properly categorized information, but use it efficiently in mission planning and execution.

- Current and proposed commercial communications and information management systems have revolutionized the environment and offer unique leverage and synergy opportunities for the Air Force.

- Dedicated Air Force space systems will not provide the backbone for future C^2 and information management architectures and cannot satisfy all user high-data-rate, survivable, wide-bandwidth and low probability of intercept (LPI) communications requirements.

- Air Force space and information budgets will have little to no growth through the Future Years Defense Program (FYDP) and well into the next century, barring galvanizing international circumstances threatening to our national security and way of life.

Assessment:

- Awareness of C^2 capabilities is increasing with the stand-up of AC^2ISRC. Impetus provided through the emphasis on a low-footprint, highly deployable aerospace force has pushed the community toward improving its global connectivity, high data rate, reachback capabilities, and interoperable C^2.

- However, there are Air Force space and information management shortfalls across the FYDP that will have a chilling effect on the Air Force's ability to provide a highly evolved, comprehensive, Air Force–funded information architecture.

  - Major space communications programs such as Space-Based Infrared Systems-High and -Low, Adv EHF, Gapfiller, and the Global Broadcast System are underfunded or unfunded in the outyears.
  - Major space-based information programs (such as space-based radar) that could replace or augment platform-based systems (such as JointSTARS) are not funded at all and will be additive if and when the program proceeds.
  - Major terrestrial-based information management/C^2 systems are migrating to network-centric environments with DII/GII/NII standards and will be funded from within program sources. Unfortunately, this freezes functionality improvements and enhancements as programs slip.

- There will be inadequate resources in the Air Force and DoD budgets through 2015 to fully fund MILSATCOM programs capable of providing the communications capacity required to meet the Services' and warfighter's requirements. While the NRO's National Space Communications Program has the potential to move large amounts of space information via space-based cross-linked data relays, it is not designed to provide, secure, mobile, LPI, interconnected communications.
- Future operating environments as depicted in *Joint Vision 2010* and Air Force *Global Engagement* will rely on a dynamically tasked eAF relying on information operations and warfare, information dominance, and total connectivity.

7.3 Approach to the Problem

Fully integrated information management/C^2, enabled by military and commercial space systems, will require investments in technology, systems, integrated connectivity, and task-centered databases. Operations concepts, policy, doctrine, strategy, tactics, and training need to evolve to reflect this technology-push environment.

However, the key to the success of these architectures is to leverage the revolution in commercial communications and capitalize on the ability to tap into the worldwide high-bandwidth capabilities being offered by such entities as Iridium, Teledesic, and Spaceway. This will require the Air Force to develop a comprehensive, focused business plan to access commercial service providers and to adjust Air Force acquisition, planning, and requirements processes so that commercial solutions are encouraged, funded, and implemented.

Therefore, the recommended migration approach is focused on optimizing the opportunities inherent in commercial capabilities and migrating Air Force information technology sources away from dedicated military communications satellites on to the emerging commercial backbone.

7.4 Migration Plan

The Air Force must immediately begin planning for the transition to large commercially provided information management architectures. The FY 02 program objective memorandum should reflect adjustments made in the intervening years (1999–2000) to provide the following:

1999—Begin to transition to a commercial-based “deployable” dedicated MILSATCOM program (Milstar-like) to provide dedicated mission-essential connectivity for military users.

1999—Task the National Security Space Architect to update the 1996 MILSATCOM architecture study to account for the advancements in the commercial communications community. The recommendations should be used to restructure the Air Force MILSATCOM architecture to reflect a mix of commercial and military systems.

1999—Provide a strategy-to-task analysis of the Air Force information management/C^2 architecture and be prepared to implement a comprehensive, transparent, seamless interconnected system. This should

- Enhance and exploit the DII to satisfy Air Force and AEF needs
- Establish an AEF C^2ISR system architecture that fully incorporates commercial capabilities and AEF requirements
- Develop new military value-added capabilities that integrate rate with commercial-based architectures

2000—Begin to understand and calculate the advantages of Internet-based business operations. Implementation of a virtual business center would enhance the “paperless” Air Force, improve timeliness of business transactions, expand opportunities for training and education, and underpin a revolution in operational advancements.

7.5 Technology Roadmap

A technology investment plan and roadmap needs to be more fully developed but ought to include the following:

- Capitalize on the new AFRL S&T Investment Plan that increases space and space-related funding for AFRL and the Space and Missile Systems Center top-priority efforts
- Invest $100 million a year in projects that demonstrate advanced technologies in an operational environment
- Make calculated technology investments in commercially adaptable systems and terrestrial interface equipment
- Invest in technology that improves secondary dissemination systems
- Invest in rocket propulsion, materials, and structures
- Invest in advanced communications interface units that translate different bandwidth, frequencies, and signals into common information
- Invest in a space-based dual-aperture antenna and other SBR technologies

7.6 Conclusion

The opportunity to make a transition to a more cost-effective information management/C^2 architecture is at hand. With enabling investments in technologies and the updating of planning, acquisition, and requirements processes that allow the Air Force to respond quickly to commercial business cases, the Air Force can step boldly into the 21st century by capitalizing on commercial systems to support an aerospace force.

8.0 Acquisition Strategy

8.1 Acquisition Reform to Accept New Commercial Business Cases

Budget pressures are forcing the Air Force to earnestly reevaluate its priorities to meet a changing and arguably less stable geopolitical environment for the 21st century. Coupled with the inexorable momentum to downsize force structure and shed non–value added programs and operations, aerospace forces must reorient to become a more agile, fluid, and dynamic force. Can the technologies and programs needed to support this new aerospace force be acquired and implemented within projected flat budgets?

The answer is Yes! The Air Force can evolve into an aerospace force and field new space and information management systems within the projected budgets. However, this can be done only if the Air Force buys smartly—that is, uses commercial-like practices, reinvents its requirements practices, and follows an integrated, system-of-systems approach. Stovepiped requirements, planning, acquisition, and operations will not provide the efficiencies needed to field the new systems.

The Air Force is obligated to comply with the Federal Acquisition Regulations and the DoD 5000-series acquisition regulations. Inherent in the history of DoD acquisition policies and regulations and current practices are principles that tend to inhibit the Air Force from fully exploiting commercial practices. A culture has developed within the Service and in Congress that adheres to rigorous, inflexible, heavily encumbered acquisition and contracting practices. This culture has no incentive to earnestly look to commercial systems and practices for solutions. Our Air Force space community is simply not postured to respond in an agile manner to the emerging technology and systems revolution in commercial space and information management systems.

Several revolutionary acquisition approaches can help the community be responsive to “commercial-like” practices and streamline routine Air Force acquisition practices. For example, Section 845 of PL 103-160 allows the Air Force to enter “other transactions” for prototype projects. This is a non–Federal Acquisition Regulations based agreement for weapon systems proposed to be acquired or developed by DoD. Prototypes are not defined in public law, though they can be generally described as an end product that reasonably evaluates the technical feasibility or operational military utility of a concept or system. Some transactions may not be appropriate for every award, but they provide a flexible vehicle when needed.

Another acquisition strategy is to use phased, streamlined development approaches leading to Services’ capabilities. A modular building-block approach with companion service modules can focus early industry involvement scope while minimizing development risks and capitalizing on commercial best practices. The evolved expendable launch vehicle management structure is a good example of a streamlined business strategy.

In addition, a culture shift needs to occur within the Air Force acquisition and contracting community to promote, advertise, and support the buying, leasing, or procuring of commercial products and services. Guidelines, symposia, and education efforts should be instituted that literally change the way Air Force personnel think about commercial-like practices. This should be a standalone subject at a future CORONA to ensure senior leader buy-in.

Finally, the Air Force should establish a dedicated $100 million yearly effort specifically aimed at developing and infusing commercial technology and prototypes into the Air Force development and operational environment.

In summary, a streamlined, transparent acquisition strategy designed and implemented to foster commercial-like practices should be established. This will drive a change in cultures to give program directors an incentive to look upon acquisition, planning, and requirements processes with a clear eye, not toward “faster, better, cheaper” but toward “integrated, commercial-like, and best value.”

Table F-9. *AIM Findings and Recommendations*

Finding AIM #13: The acquisition and requirements generation processes are not designed to incorporate commercial space opportunities across the Air Force mission areas. The communication revolution already has provided most of the technology needed by the Air Force for the Air Expeditionary Force. The challenges are to choose affordable implementation, innovative application—and information management needs the most development—to build a little, and to test a little, aggressively.

- **Recommendation AIM #13a:** Task AQ, XP, and XO to reorder their processes to ensure that commercial options be considered during the requirements generation, planning, and acquisition processes. Chief of Staff of the Air Force policy directing commercial systems, products, and services should be the first choice with cost and functional trades used to justify movement off commercial space products.
- **Recommendation AIM #13b:** For launch and communications, baseline the use of commercial systems except when one of the following applies: the system is directly involved in combat tasks, the military mission is critical and commercial systems imperil lives or success, or the operator is directly at risk from an enemy threat.
- **Recommendations AIM #13c:** On an immediate and ad hoc basis, develop end-to-end concepts that can exploit available commercial systems, such as:
    - Partner with industry to remain up to date on technological developments
    - Identify commercial systems with useful capabilities during contingency, and develop operational concepts to integrate them with military operations
    - Identify, develop, and acquire the important interfaces, ground equipment, and procedures to rapidly integrate commercial systems into military operations
    - Develop rapid contractual procedures to obtain commercial systems
    - Encourage interoperability standards in critical areas, such as ground terminals

Table F-10. *AIM Findings and Recommendations*

Finding AIM #14: The current Air Force program element structure does not support the acquisition or fielding of warfighting C^2 systems across the air, space, and cyber environment.

- **Recommendation AIM #14a:** Align C^2 funding under one C^2 panel for oversight.
- **Recommendation AIM #14b:** Create a $100 million budget line item to fund and field rapid-response needs across the air, space, and cyber environment, capitalizing on the incredible commercial product cycle times (similar to the Army program).

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Annex 1 to Appendix F

AIM Panel Meetings

DATES	LOCATION	ORGANIZATION	TOPIC	POC
12–13 Feb 98	Washington, DC	SAB	Kick-Off	n/a
10 Mar	Chantilly, VA	NRO	Architectures	Mr. Rich Haas
19 Mar	Tampa, FL	U.S. Central Command	Command Overviews	
		U.S. Special Operations Command	Warfighter Requirements	
14–16 Apr	Langley AFB, VA NRL, Washington, DC	ASC^{2}A	C^2 Vision, CONOPS	Col Richard Webber
		U.S. Army Training and Doctrine Command	Army Future Concepts	Lt Col Bob Leonhard
		U.S. Army Space and Missile Defense Command	Army Space Future Operational Capabilities	Lt Col Gary Trinklein
		Electronics Systems Command	C^{4}I Tech/Architectures	Mr. Seymour Friedman
		AFRL	Air Force C^{4}I R&D Initiatives	Mr. John Graniero
		Naval Research Laboratory	Navy C^{4}I R&D Initiatives	Mr. Glenn Cooper
		Assistant Secretary of the Air Force, Acquisition, Space and Nuclear Deterrence	Air Force Space Programs	Maj Denise Knox
21–24 Apr	Schriever AFB, CO	SAB	Spring Board	Gen Estes
		U.S. Space Command	Long Range Plan	Maj Gen Woodward
		Air Force Space Command	Strategic Plan	Brig Gen Morehead
		Space Warfare Center	Overview	
		BMDO	Overview	
		11th Space Warning Squadron	Attack and Launch Early Reporting to Theater (ALERT) Overview	
		Air Force Battlelabs	Overview	
12–14 May	Vandenberg AFB, CA	14 Air Force	AFSPACE C^2 Overview	Maj Gen Perryman
		Space and Missile Systems Center	Program Reviews	Col Bob Cox
		JCS/C^4 Systems Space Directorate	MILSATCOM Program	Maj Justin Keller
		AFRL	Air Force C^{4}I R&D Initiatives	Dr. Warren Debaney
4–5 Jun	Washington, DC	DISA	Comm/Info Programs	Dr. Pravin Jain
		Naval Research Laboratory	Partnerships; Info Tech	Mr. Mark Powell
		Chief of Naval Operations/ Director of Communications	Navy SATCOM Programs	CDR Dave Creasy
		NRO	Space/Tech Alliance	Mr. Ben Gimeno
		Air Force CIC	Air Force Deployable Comm	Lt Col Roy King
		Electronic Systems Command/Expeditionary Force Experiment (EFX) System Program Office	EFX Comm Initiatives	Maj Rick Painter
14–25 Jun	Irvine, CA	SAB	Summer Study	n/a

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Annex 2 to Appendix F

Acronyms and Abbreviations

AC^{2}ISRC	Aerospace Command and Control and Intelligence, Surveillance, and Reconnaissance Center
AEF	Aerospace Expeditionary Force
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AIM	Architecture and Information Management
ASC^{2}A	Air and Space Command and Control Agency
AWACS	Airborne Warning and Control System
BMDO	Ballistic Missile Defense Organization
C^2	Command and Control
C^{2}ISR	Command and Control Intelligence, Surveillance, and Reconnaissance
C^{4}I	Command, Control, Communications, Computers, and Intelligence
C^{4}ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CIC	Combat Information Center
CII	Common Information Infrastructure
CINC	Commander in Chief
CJCS	Chairman, Joint Chiefs of Staff
COA	Course of Action
COE	Common Operating Environment
CONOPS	Concept of Operations
CONUS	Continental United States
COP	Common Operational Picture
DARPA	Defense Advanced Research Projects Agency
DDR&E	Director of Defense Research and Engineering
DGG	Defense Global Grid
DII	Defense Information Infrastructure
DII COE	Defense Information Infrastructure Common Operating Environment
DISA	Defense Information Systems Agency
DISN	Defense Information Systems Network
DMS	Defense Messaging System
DoD	Department of Defense
DSCS	Defense Satellite Communications System
DSN	Defense Switched Network
eAF	expeditionary Air Force
EELV	Evolved Expendable Launch Vehicle
EFX	Expeditionary Force Experiment
EHF	Extremely High Frequency
FCC	Federal Communications Commission
FYDP	Future Years Defense Program
Gbps	Gigabits per Second
GBS	Global Broadcast System
GCCS	Global Command and Control System

GCSS	Global Combat Support System
GII	Global Information Infrastructure
GPS	Global Positioning System
IP	Internet Protocol
IR&D	Independent Research and Development
ISR	Intelligence, Surveillance, and Reconnaissance
ITU	International Telecommunications Union
IW	Information Warfare
JCS	Joint Chiefs of Staff
JFC	Joint Force Commander
JointSTARS	Joint Surveillance, Target, and Attack Radar System
JSEAD	Joint Suppression of Enemy Air Defenses
JTAMD	Joint Theater Air and Missile Defense
LPI	Low Probability of Intercept
MILSATCOM	Military Satellite Communications
MRC	Major Regional Conflict
NASA	National Aeronautics and Space Administration
NCA	National Command Authority
NCC	Network Control Center
NII	National Information Infrastructure
NOAA	National Oceanic and Atmospheric Administration
NOSC	Network Operations and Security Center
NRO	National Reconnaissance Office
NTIA	National Telecommunication and Information Administration
OSI	Open System Interconnection
PC	Personal Computer
PGM	Precision-Guided Munition
R&D	Research and Development
RLV	Reusable Launch Vehicle
RMA	Revolution in Military Affairs
S&T	Science and Technology
SAB	Air Force Scientific Advisory Board
SATCOM	Satellite Communications
SBIRS	Space-Based Infrared System
SHADE	Shared Data Environment
STA	Space Technology Alliance
TBM	Theater Ballistic Missile
TIA	Telecommunications Industry Association
UAV	Unmanned Aerial Vehicle
USA	United States Army
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
VSAT	Very Small Aperture Terminal
VTC	Video Teleconferencing
WMD	Weapons of Mass Destruction

Appendix G

Payloads

1.0 Introduction

The Payloads Panel examined topics of significance to defense missions that either currently have a space segment or might, in the view of the panel, justify a space segment in the future.

Historically, Department of Defense (DoD) missions have taken advantage of the high ground of space to collect—with passive receivers—electromagnetic energy that passes easily through the earth's atmosphere (visible, infrared [IR], and radio frequency [RF]) for electronic intelligence, communications intelligence, imagery intelligence, measurement and signals intelligence, weather forecasting, and warning. The receivers relay radio-frequency communications with relatively low-power spacecraft (10^2 to 10^3 watts [W]) to provide precision passive terrestrial navigation through one-way range measurement based on precision timing distributed from space.

While commercial forces have increased spacecraft total power to approximately 10^4 watts and, through increased demand for commercial launch services, stimulated a significant drive toward lower-cost launches, there is no foreseeable scenario in which payload weight and power consumption are not major constraints on space system design.

In structuring this study of payloads for the future, existing missions with space segments were parsed into their basic elements to allow the generic underlying science, technology, engineering, and art to be dealt with as they might be applied across multiple missions and applications. Thus the current space missions, including communications, intelligence, weather, surveillance/warning, and navigation, are mapped into technology areas. This study is not comprehensive in the sense that not all current space missions were examined in depth to suggest appropriate payloads for future missions. The sections individually focus on major payload investment areas of the near term, system architecture and integration issues, and technologies of interest for the future.

This appendix is divided into the following sections:

1.1 Payloads Panel Membership

Dr. Llewellyn S. Dougherty, Chair
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Vice President, Engineering (Ret)
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Technical Writer: Capt D. Brent Morris, USAFA/DFP

2.0 Space-Based Radar

2.1 Scope and Content

This section discusses SBR with an emphasis on ground moving-target indication (GMTI) and synthetic-aperture radar (SAR) imaging. Topics include potential SBR modes of operation, concepts of operations (CONOPS) for SBRs, potential SBR architectures, critical SBR technologies, SBR efforts, and recommendations.

2.2 Structure

We begin by reviewing the basic modes of radar that have potential application from space. These modes include GMTI, SAR, and airborne moving-target indication (AMTI). We then discuss issues that drive the development of CONOPS and architectures for an SBR system, such as cost and fusion with existing moving-target indication (MTI) and SAR assets. Next, we consider a few key technologies that should have application to nearly any SBR system that is deployed. Development efforts for these technologies should lead to lower-cost and higher-capability systems. Next, we provide a description of current and recent efforts in SBR. Finally, we draw conclusions and make recommendations on how an SBR system should be developed and fielded.

2.3 SBR Modes of Operation

2.3.1 Synthetic-Aperture Radar

SAR is a mode of operation in which the radar transmits and receives multiple pulses while traversing the area of interest. The pulses are then processed to produce a radar map (or “image”). SAR can operate in several modes, depending on how many pulses are collected to produce an image. By collecting more pulses (over a longer baseline), SAR can form a higher-resolution image. If large areas are to be imaged, fewer pulses are typically collected, resulting in lower-resolution images.

Most military SAR imagery is performed by airborne platforms, such as Joint Surveillance, Target, and Attack Radar System (JointSTARS) aircraft and other national assets. Space-based imagery for American military use has historically been the responsibility of the National Reconnaissance Office (NRO). Discussion of the NRO’s capabilities and future plans exceeds the security classification of this appendix. However, any serious consideration of SBR for defense applications should include the possibility of combined architectures to serve the intelligence community and the military. Although their requirements may differ in nature and detail, there is inevitably substantial overlap in the solutions, and significant economy to be gained from shared use of the resources.

Virtually all current SBR systems are SAR imagers. An example of a current space-based SAR is the Canadian RADARSAT-1. RADARSAT-1 is an advanced earth observation satellite project developed by the Canadian Space Agency to monitor environmental change and to support resource sustainability. The National Aeronautics and Space Administration (NASA) launched RADARSAT-1 on 4 November 1995 in exchange for pro rata access to the satellite through the Alaska SAR Facility. RADARSAT-1 was placed into a sun-synchronous polar orbit and provides global coverage. It has a design lifetime of 5.25 years. Figure G-1 shows the various resolution modes of the SAR. RADARSAT-2 is scheduled for launch in 2001, and will provide improved resolution. Preliminary plans also call for a GMTI capability on RADARSAT-2.

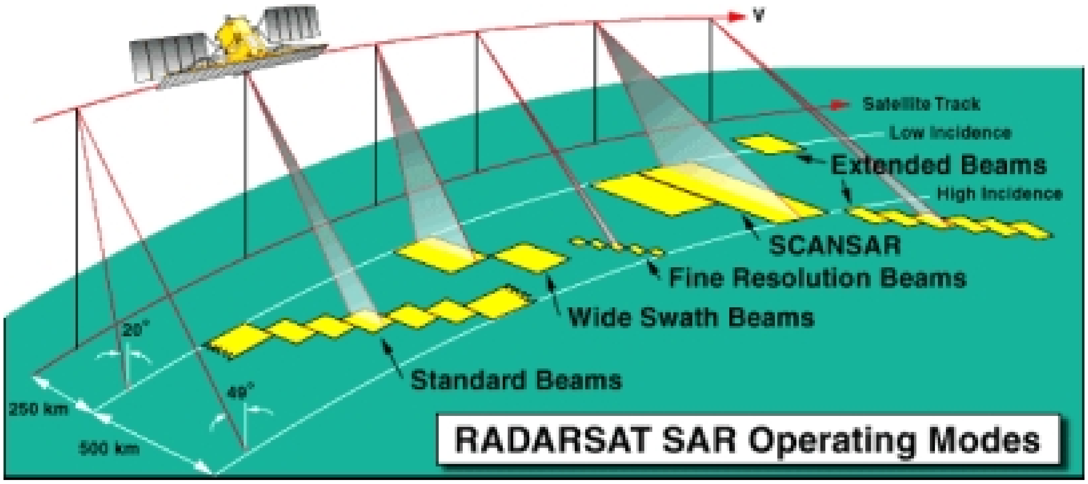

Figure G-1. *RADARSAT-1 SAR Operating Modes*[1]

2.3.2 Moving-Target Indication

SARs form images of the ground and stationary objects on the ground. In the time it takes a moving SAR to transit enough physical space to create an image from the energy it receives along its path, moving targets on the ground become blurs in the image and may disappear entirely. The Doppler modulation of the radar signal return, caused by the targets' motion along the line of sight to the radar, can be used to detect moving targets and discriminate them from the ground return. This is a well-developed technique used by airborne radars to detect airborne targets (via the Airborne Warning and Control System [AWACS] and E-2C platforms) and ground moving targets (via JointSTARS). These airborne radar approaches can be scaled for use on space platforms with somewhat longer ranges and much higher platform velocities.

Moving-target detection typically uses very short integration intervals versus the longer intervals used to generate SAR imagery. Since the integration interval is significantly shorter for MTI, the net change required to scale an imagery radar to perform moving-target detection is an increase in power aperture. Additionally, the ground's Doppler return imposes slightly different field-of-regard constraints for the two types of radar operation. The moving-target radar cannot see too close to its own nadir direction, since the moving targets provide minimal Doppler shift relative to ground clutter. Its field of regard is a toroid or doughnut between a minimum and maximum grazing angle. The imagery radar cannot see clearly too close to the direction of its own motion. Its field of regard is like a pair of butterfly wings projected on the ground to either side of its flight path. The two modes of operation are illustrated in Figure G-2. Both modes are compatible from a single satellite, but require different constellation optimization to provide economical coverage by the entire constellation. Typically, the number of satellites needed to provide useful moving-target information is much larger than the number needed for useful imagery information, so that the MTI requirement dominates the optimization.

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[1] Canada Centre for Remote Sensing, http://www.ccrs.nrcan.gc.ca/ccrs/tekrd/radarsat/specs/radovere.html.

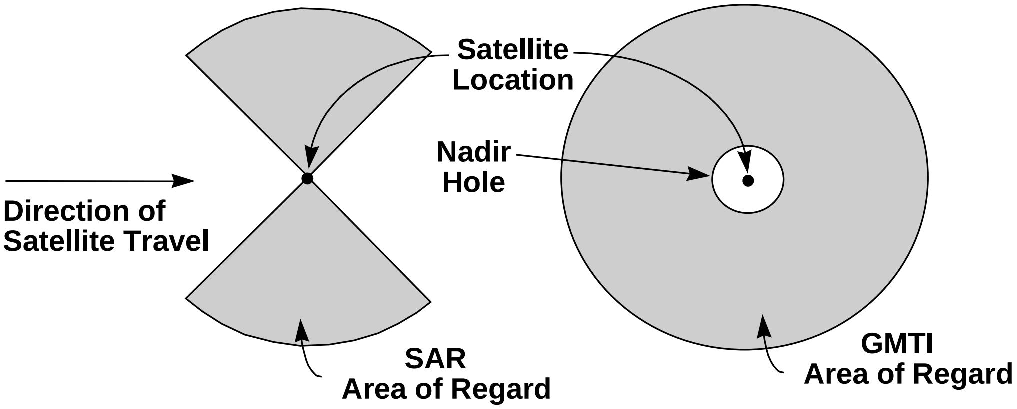

Figure G-2. *SAR and GMTI Radar Modes*

2.3.2.1 Ground Moving-Target Indication

GMTI is performed well from the JointSTARS airborne platform. If GMTI with target detectability that is similar for the targets of interest is performed from a satellite platform, the power and aperture must be increased relative to JointSTARS. Well-documented satellite and constellation designs for performing GMTI from space are available from the Discoverer II Joint Program Office,[2] Air Force Research Laboratory (AFRL),[3] and the Air Force Space and Missile Systems Center (SMC).[4] Space-based GMTI can be used for a variety of purposes. For small constellations, SBR satellites can be used to provide periodic deep looks at areas well beyond the range of JointSTARS, early periodic looks at areas to which JointSTARS is en route, and periodic looks in regions where the aircraft cannot be deployed. If the SBR constellation is large enough, it can be used to provide full GMTI functionality, including battlefield surveillance, targeting, and other JointSTARS-like sensing functions. However, SBR cannot fully replace JointSTARS, since the airborne platform performs other nonsensor functions such as command and control. Replacement of JointSTARS would require migrating these command and control functions to an alternative platform or ground station.

2.3.2.2 Airborne Moving-Target Indication

Airborne moving targets, airplanes, and cruise missiles represent, on the whole, a substantially larger, more demanding surveillance problem than ground moving targets. The radar fundamentals are the same. However, the revisit rates need to be faster in local areas, and the overall coverage areas generally are larger due to higher target speeds. The higher target speeds also slightly ease the difficulty of detection in clutter, and range gating can sometimes be used to significantly reduce ground clutter. However, the air moving targets can have substantially smaller radar cross sections (RCSs), particularly if they are designed for low observability. Because of all these effects, the AMTI radar will ordinarily operate at a much lower frequency and require a much larger power aperture than GMTI radar. A larger constellation than those proposed for GMTI would be needed to provide useful AMTI data. A moderately sized constellation could potentially be used to provide “trip-wire” coverage, for example, to monitor aircraft crossing the perimeter of no-fly zones and to provide periodic looks at airfield activity. Significantly larger constellations would be required to provide the sensor functionality of AWACS.

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[2] DARPA, TTO/DJPO, 3701 N. Fairfax Drive, Arlington, VA 22203-1714, (703) 526-1701.
[3] AFRL/VSSS, 3550 Aberdeen Ave. SE, Kirtland AFB, NM 87117-5776, (505) 846-4495.
[4] SMC/XR, 2430 El Segundo Blvd., El Segundo, CA 90732, (310) 363-5436.

2.4 SBR Concepts of Operations

There are a wide variety of potential CONOPS for SBR systems. These CONOPS depend on the SBR's mode of operation (SAR, GMTI, AMTI, or some combination of the three). For the near term and through 2010, it appears that SAR and GMTI are the most likely functional candidates for an SBR system, and these functions will be emphasized in this subsection.

2.4.1 Relationship to System Architecture

System CONOPS will drive the architecture of an SBR system. If the CONOPS for the SBR system includes using it to provide sensor data for directing battlefield engagements, then the architecture will be required (nearly) continuously to have a satellite in view of the theater. On the other hand, if the system is to be used solely to give periodic looks at what is happening in the deep theater, satellites will only need to be in view occasionally, perhaps every several hours. The needed revisit rates for various GMTI and SAR tasks are being studied by multiple organizations, including Air Force Space Command (AFSPC), Air Combat Command (ACC), Electronic Systems Center (ESC), and SMC. Because CONOPS is such a significant driver to system architectures, it is imperative that a CONOPS be developed (at least to a preliminary level) prior to the design and development of an operational SBR system.

2.4.2 Methods of Development

CONOPS development for SBR is immature. Two primary studies have been conducted thus far, and a third is in progress. In 1997, two quick-look studies were performed. AFSPC and ACC performed a joint CONOPS study with participation by SMC, NRO, the Defense Advanced Research Projects Agency (DARPA), the Secretary of the Air Force/Acquisitions, AFRL, and industry. This study resulted in a document entitled "Concept of Operations for the Spaced Based Moving Target Indicator System," which has been approved by AFSPC and ACC.[5] A second study was completed in 1997 by the Office of the Assistant Secretary of Defense (OASD) Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance staff. This "MTI Requirements Analysis Study (MRAAS)" looked at SBR as one part of an overall MTI collection system, including space, unmanned aerial vehicle (UAV), air, and ground assets.[6] A third study is ongoing with the SBR Integrated Product Team (IPT) at AFRL. This study takes a comprehensive look at both system architectures and CONOPS from a requirements perspective. One could choose any of these three studies as an initial point from which to evolve CONOPS.

CONOPS can evolve in several ways. One of the least expensive methods is via modeling and simulation. Several modeling and simulation tools detailed later are currently available or in development for SBRs. Simulations can include the technical capability of the SBR constellation (for example, what is the probability of detecting a target?) as well as the military utility of the constellation (for example, by how many days would the SBR constellation shorten the war?). These simulations are typically based on established warfighting doctrine with little or no user interaction during the actual simulation.

On a more detailed level, models can be developed that allow man-in-the-loop simulations. For example, a simulation might allow an operator to task the radar constellation to look at a specific region. The model might then be used to simulate (1) the delays associated with getting the tasking to the satellite constellation, (2) the orientation of the appropriate satellite to look at the location, (3) waiting for the satellite to come into view, (4) a statistical determination of the satellite's detecting targets or generating false alarms, and (5) the processing and relaying of the information back to the user. The satellite-

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[5] AFSPC/DO, 150 Vandenberg St., Suite 1105, Peterson AFB, CO 80914-4500, (719) 554-3100.

[6] This document is available from OASD/C^3ISR, 1931 Jefferson Davis Highway, Arlington, VA 22202-5291, (703) 607-0285.

generated information could then be displayed to the user as part of a fused common operational picture. By "interacting" with the SBR system in a simulated wartime environment, the operator can provide useful feedback for evolving the SBR CONOPS. This type of simulation can also be used to validate proposed human-system interfaces to the SBR system.

At a still higher level, an actual hardware SBR demonstration program can be used experimentally to evolve CONOPS. As an example, the final CONOPS for the JointSTARS was not fully developed until several years after the first aircraft had been fielded and used in actual wartime operations. It is anticipated that any SBR CONOPS that is developed will be heavily influenced by the Discoverer II demonstration program, scheduled for first launch in 2003 and operational testing and analysis through 2005. In addition to the obvious benefits of using a demonstration system to evolve CONOPS, the Discoverer II effort will provide system cost and technical performance criteria critical to deciding whether and when to field an operational SBR system.

2.4.3 Critical Factors in Developing CONOPS

Regardless of how the system CONOPS is developed, several issues are key. First, the SBR must be designed to fit into a system-of-systems architecture (SOSA), which includes sensors from space, UAVs, and air, ground, and naval assets. As such, the SBR must be able to provide data to a network-centric communications architecture, which can interpret the data at a central or distributed fusion and processing location. It is anticipated that all sensors in the SOSA will feed this fusion and processing location. Ideally, MTI and SAR data provided by air and UAV platforms will have similar formats to MTI and SAR data provided by SBR. Data protocols need to be established up front and early in order to influence the design of an SBR system (as well as to influence future airborne platform upgrade efforts). Additionally, even if the SBR system has a capability to downlink data directly into theater, it must also input those data into the network-centric communications architecture. Similarly, tasking of the satellite constellation (as well as tasking of air assets) should be possible through the network-centric communications architecture. Finally, the SBR system must be accessible and responsive to the warfighter (Air Force, Army, Navy, expeditionary, and coalition forces). Warfighters must be able to task the system and receive information from it seamlessly. The actual routing of tasking and data is not as important as the accessibility to the system. This paradigm can be likened to the method of telephone communications today. When the user picks up a phone, it is unimportant to the user how the call gets routed as long as the service is there when needed. Because the network-centric information structure is crucial not only to an SBR architecture but also to any planned upgrades to current systems (for example, AWACS and JointSTARS), it is imperative that the communication structure protocols be developed as soon as possible.

2.5 SBR System Architectures

2.5.1 Dependency on CONOPS and Cost

The SBR system architecture will be driven by CONOPS and cost. Thus, it is critical that the Air Force develop a system CONOPS before developing and approving overall system architecture. Because individual satellites are expensive, it is likely that the initial SBR CONOPS will be for a system with a small number of satellites that augment JointSTARS by providing deep-look theater access and periodic access in locations where JointSTARS is not deployed. If an augmentation CONOPS is developed, the Air Force should design individual satellites so that the system is scalable—that is, can perform more and more JointSTARS-like (GMTI and SAR) sensing as additional satellites are launched. Designing scalable satellites will give decision makers the option of growing the satellite constellation into an eventual (long-term) replacement system for JointSTARS sensor functionality. In the near to mid-term, an augmentation system may allow for the use of fewer JointSTARS platforms, or for a decreased operational tempo for JointSTARS crews. For the longer term, a system that scales to include AWACS-like AMTI sensing should be investigated. Ideally, over the long term, the initial GMTI and SAR system will gracefully increase its capability to include AMTI sensing as satellites are added and block changes are made.

2.5.2 Orbital Tradeoffs

2.5.2.1 Low Earth Orbit (LEO) vs. Medium Earth Orbit (MEO) vs. Geosynchronous Earth Orbit (GEO)

As satellite altitude increases, the number of satellites required to provide a given revisit rate decreases. However, LEO satellite architectures provide several advantages for both GMTI and SAR. Low-altitude architectures reduce individual satellite size, weight, power, and aperture requirements. This makes per-satellite costs smaller while increasing the number of satellites required to perform a given mission. Most designs in recent years have been for below 1,000 nautical miles, but a few designs have been proposed at higher altitudes.[7] Benefits of a LEO-based architecture include smaller footprints on the ground (more focused surveillance), faster formation of SAR images due to faster transit across a given ground track, better jamming resistance due to more limited view of the satellite from earth, a much reduced radiation environment relative to higher orbits, and a more graceful degradation of the overall system should a single satellite fail. Challenges associated with LEO architectures include demands on batteries due to frequent eclipse cycles, and a large-clutter Doppler spread due to the relative ground speed of the LEO satellites. Examples of proposed LEO constellations include a 24- to 48-satellite constellation proposed by the Discoverer II Joint Program Office[8] and an 18- to 36-satellite constellation proposed by AFRL, called the Space Electronically Agile Radar (SPEAR).[9]

2.5.2.2 Latitude Coverage

If global coverage is not required, the number of satellites required to perform coverage of a given region with prescribed minimum gaps in coverage can be reduced. For example, the Discoverer II proposed satellite constellation is sized to provide an average 15-minute gap in SAR imagery coverage, but only as an average between the latitudes of 65° North and South. If global coverage were required with the same 15-minute-average gaps, the number of satellites required would necessarily increase. The decision on reduced latitude coverage must be made on the basis of how the system is to be used (i.e., CONOPS).

2.5.3 Collection Techniques—Monostatic vs. Bistatic vs. Multistatic vs. Passive Coherent Location (PCL)

Monostatic SBR uses the same satellite for both transmit and receive, while bistatic SBR uses separate transmit and receive satellites. Multistatic systems use multiple transmitters or receivers, as shown in Figure G-3.

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[7] See the *Surveillance and Threat Warning Development Plan,* available from SMC/XR.

[8] DARPA, TTO/DJPO.

[9] AFRL/VSSS.

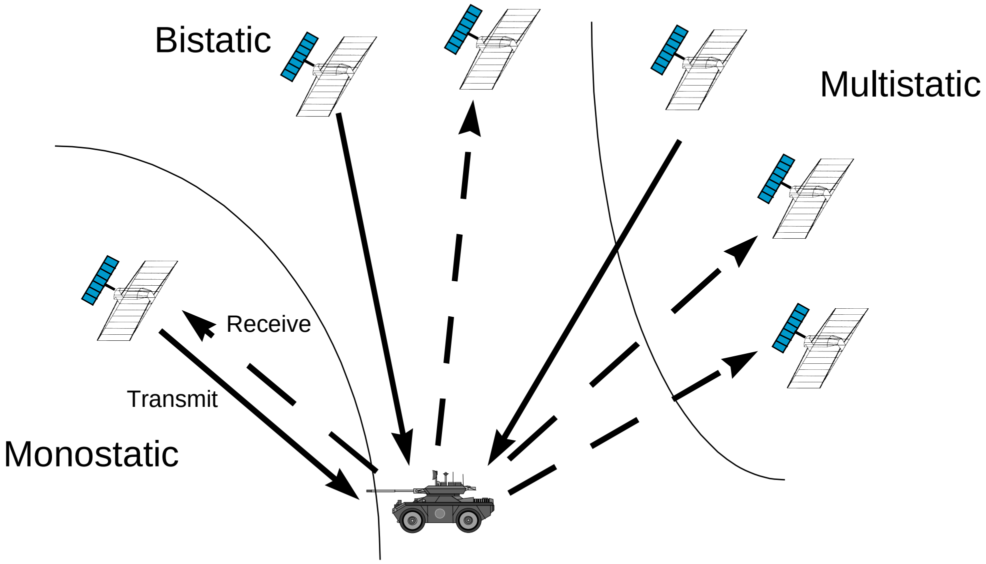

Figure G-3. *SBR Collection Techniques*

Each collection method has potential advantages and disadvantages. Monostatic SBR is the simplest to design since there is no need to provide detailed timing information to coordinate transmit and receive platforms and register received targets against transmitted pulses. The target registration problem can be very complex if there are a large number of targets in the field of view (FOV) of a bistatic or multistatic radar, particularly if there is any considerable error probability in target locations. Additionally, monostatic radar has inherently better clutter suppression than bistatic radar because the monostatic transmit and receive beam patterns are "matched," providing two-way sidelobe suppression. Certain clutter-suppression techniques, such as the displaced phase center antenna method[10] used by JointSTARS, are based on monostatic radars.

Bistatic and multistatic systems may be able to use less transmit power by placing the receiver platform at a much lower altitude than the transmitter platform.[11, 12] Additionally, receivers for a bistatic system could be placed on airborne platforms to provide better detection of low-RCS targets. However, these airborne receivers could also be used to bistatically collect returns from a monostatic SBR, probably with better results (versus a system designed to operate solely in bistatic mode) since a monostatic system would inherently use a higher-powered transmitter than a bistatic system. Some research has shown the potential for target RCS improvements (called blooming) with bistatic radar. However, most of this research has been for airborne versus ground targets, and the bistatic geometries required to produce blooming are unlikely for ground targets.

Since current technology appears to support the feasibility of building a monostatic GMTI SBR, and because the Discoverer II program will demonstrate monostatic GMTI from space, it is anticipated that the operational GMTI follow-on system to Discoverer II will be monostatic. However, there may well be bistatic collectors mounted on air platforms to give additional GMTI capability by receiving signals from the monostatic SBR system. These receivers could also demonstrate the feasibility of designing a bistatic AMTI SBR in the future.

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[10] S. A. Hovanessian, *Detection of Moving Targets in Mainlobe Clutter Region by Spaceborne Radars,* Aerospace Technical Report #TOR-0086A(2503)-2.

[11] G.L. Guttrich et al., "Space/UAV Bistatic Theater Surveillance," Presentation at NATRAD '97, Colorado Springs, CO.

[12] Guttrich et al., *Wide Area Surveillance Concepts Based on Geosynchronous Illumination and Bistatic Unmanned Airborne Vehicles or Satellite Reception,* available from the MITRE Corp., 202 Burlington Road, Bedford, MA 01730.

PCL is a passive bistatic method that uses transmitters of opportunity (such as radio stations) and dedicated receivers. It is generally accepted that PCL is not suitable for GMTI, but it may be useful for AMTI. Since this appendix is primarily concerned with GMTI and SAR, PCL will not be considered here. However, references for PCL and a sample design are contained in the *Surveillance and Threat Warning Development Plan*.

2.5.4 Single Satellite in Field of View of Target vs. Multiple Satellites

It may be advantageous (in terms of capability and cost) to have more than one satellite in the FOV of an area of interest. Having two satellites in the FOV provides for interferometric SAR capability, which yields significant improvements in SAR resolution. The Discoverer II program will demonstrate this capability. One recent study showed that for AMTI, it may be less expensive to field a very large system of less capable, noncoherently "cooperating" satellites versus a smaller constellation of highly capable satellites.[13] This large constellation would use an "*m* of *n*" detection method: if *m* satellites out of *n* satellites in the FOV detect a target, then a detection is declared. (For example, a three-of-five detection method would assume that five satellites were in the FOV, and if three, four, or five of those satellites detected a target, then a detection would be declared.) This detection method allows for individual satellites to have a lower probability of detecting a target while maintaining a high combined probability of detection. The study showed that a reduction up to 40 percent in overall system cost could be realized using this method for an AMTI system, due to lower individual satellite costs combined with economies of scale. Further study of this concept is warranted for GMTI applications.

2.5.5 Cost as an Independent Variable

Overall system cost will likely be one of the most important factors in developing an SBR system architecture. The cost-as-an-independent-variable analysis should be based on total system life-cycle costs of the SBR constellation (versus looking only at the cost of manufacturing the individual satellites) and should include all associated segments of the SBR system. In addition, consideration should be given to potential savings if one or more fleets of airborne or UAV platforms (and associated deployment and maintenance costs) can be downsized with the advent of SBR, or if airborne operations can be scaled back.

2.6 SBR Satellite Critical Technologies

Regardless of the architecture, certain technologies will likely be critical to making the final system more affordable or more capable. The following subsections discuss these technologies.

2.6.1 Phased Arrays

Phased arrays are the most common antennas proposed for an SBR system. Because they can be electronically steered very rapidly, two-dimensional (2-D) phased-array antennas provide the flexibility and capability to cover large areas quickly, as well as to scan diverse hot spots within an overall area of interest without having to be moved mechanically. However, phased arrays can be very expensive and heavy due to the large number of transmit/receive (T/R) modules needed. For example, a study performed in 1996 by AFRL with participation from recognized experts in the field indicated that a 6- by 22-meter (m) X-band 2-D phased array would be needed to perform GMTI in a manner that could eventually lead to full GMTI functionality from space. At this band (e.g., 10 gigahertz [GHz]), with half-wavelength element spacing, more than 500,000 T/R modules would be required for a fully populated

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[13] Dr. Daniel Hastings and Lt. Douglas Wickert, "Space Based Radar—System Architecture Design and Optimization for a Space Based Replacement to AWACS," available from the Space Engineering Research Center, Space Systems Laboratory, MIT Department of Aeronautics and Astronautics, 77 Massachusetts Ave., Cambridge, MA 02139.

phased array. Techniques such as thinning and subarraying individual T/R modules to multiple radiating elements via corporate feeds can be used to reduce this number by 50 to 80 percent or more. Even with these techniques, it is apparent that low-cost, lightweight T/R modules are critical to the objective system if 24 or more 2-D phased-array satellites are to be fielded eventually. AFRL and industry are performing research in this area. AFRL has produced (in limited quantities) space-qualified X-band receive-only modules using 0.14 watt power, with a mass of 1 gram. Lockheed Martin is currently producing 6-W C-band T/R modules for less than $400 each at a production rate of 30,000 per year. Hughes and Harris also have ongoing T/R module programs. Several contractors have predicted that a T/R module will cost (for SBR applications) about $100 within 5 years. Cost must continue to decrease, and production capability increase, if a full constellation of phased-array SBR systems is to be fielded.

In addition to component development, large lightweight antennas are needed for phased arrays. In order to maintain beam-forming accuracy, these antennas must either be stiff (on the order of 1 millimeter [mm] flexibility for a 20-m X-band antenna) or have built-in deformation measurement systems for calculating necessary phase corrections. The Discoverer II program plans to allow up to 3-centimeter (cm) flexibility with measurement systems capable of measuring deformities to 1 mm. AFRL's Transmit/Receive Antenna Module (TRAM)[14] program has a goal of a 20-m antenna with stiffness to support 1-mm maximum twist errors and $\lambda/50$ root-mean-square roughness. The TRAM program incorporates lightweight T/R modules, at a total antenna weight of 6 kilograms (kg)/m^2. AFRL has scheduled initial on-orbit component testing for 1999 with a subscale receive-only phased-array antenna.

2.6.2 Power Systems

Most proposed GMTI/SAR constellations call for LEO satellites to keep power-to-aperture requirements relatively low. This altitude places serious demands on power generation systems due to frequent eclipse and deep discharge of energy storage systems. Energy storage units must be capable of operating for 10 to 15 years with multiple eclipses per day, and potentially multiple deep charge or discharge cycles per day, particularly during conflict. Potential energy storage devices include batteries, flywheels, and solar-thermal systems. AFRL is investigating batteries, flywheels, and high-efficiency (greater than 30 percent) solar cells. AFRL anticipates developing solar cells capable of producing 100 W/kg, and lithium-ion (Li-ion) batteries capable of storing 100 watt-hour (Whr)/kg. Solar thermal power is being investigated by the NASA Lewis Research Center. The Integrated Power and Attitude Control System program is investigating a combined flywheel energy storage and attitude control system, with significant potential for reducing overall satellite bus weight.[15]

2.6.3 Signal Processing

It is anticipated that the signal processing burden associated with a large phased-array antenna will be very high. If adaptive nulling is performed on board (e.g., to mitigate jamming), large arrays of data will have to be processed in near real time. Other potential signal processing–intensive processes are clutter suppression, specialized high-resolution target detection, SAR image-processing algorithms, and adaptive phase corrections for antenna distortion. AFRL and industry continue to perform research in the signal processing area. Processing will likely require multiple hundreds of billions of floating-point operations per second with moderately radiation-hardened parts (both total dose and single-event upset). AFRL and the Discoverer II program have estimated the processing burden to be on the order of 500 to 800 billions of floating-point operations per second. Lincoln Lab predicts that these rates will be technically feasible in the 2005 time frame.[16]

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[14] AFRL/VSSS.

[15] Ibid.

[16] *Lincoln Lab Tactical Radar Program Review*, 18 June 1998, available from DJPO and AFRL/VSSS.

2.6.4 Data Communications

Depending on the eventual CONOPS selected, there may be a requirement for very high-speed data communications. If all data are to be downlinked directly to theater, with minimal on-board signal processing, a minimum downlink capability on the order of 500 megabits per second (Mbps) is required, but higher data rates are preferred. The Discoverer II program calls for a minimum 500 Mbps with a preference for higher data rates, on the order of 1 gigabit per second (Gbps). Significantly higher data rates would be better but would drive inordinately large in-theater receiving stations. However, for data linked back to the continental United States (CONUS), there is reason to look for much higher data rates, on the order of multiple Gbps. These higher data rates would allow for sending minimally processed data to a central processing location, where the latest and fastest processing algorithms could be employed by the highest-speed computers to provide the best available target detection and tracking, as well as SAR imagery. The need is for data communications equipment (e.g., cross-links, uplinks, and downlinks)—that is, high speed, light weight, and low power. The Discoverer II Program Office has suggested that the follow-on system to Discoverer II should have a mixed data distribution architecture that includes low– to medium–data rate downlinks to theater, coupled with very high data rates back to CONUS.[17]

2.7 SBR Systems, Demonstrations, and Studies

2.7.1 1995 Space Sensor Study

The 1995 Space Sensor Study[18] was an Air Force–led effort to determine the feasibility of moving the sensor functions of AWACS and JointSTARS to space. Primary study participants included AFSPC, ACC, SMC, Lincoln Laboratory, Rome Laboratory, Phillips Laboratory, Aerospace, MITRE, Jet Propulsion Laboratory (JPL), the Space-Based Infrared System (SBIRS) System Program Office, the National Air Intelligence Center, and NRO. The study investigated a wide range of AMTI and GMTI satellite radar systems and developed designs that would theoretically provide the sensing functionality of an AWACS or JointSTARS platform. Table G-1 shows the system characteristics for typical AMTI and GMTI systems developed by this study.

Table G-1. *AMTI and GMTI System Characteristics*

Mission	***JointSTARS***	***AWACS***
Altitude (nautical miles)	500–1000	1,400
Satellites (No.)	82–43	24–26
Antenna Size (m^2)	3x12	4x16
Antenna Type	Array	Array
Frequency	X-band	L-band
Satellite Weight (lbs)	6,000–10,000	30,000–40,000
Satellite Power (kW)	7–15	20–30

(Note that the data in Table G-1 are for high revisit rates and 1995 technology. Subsequent designs assuming lower revisit rates and advanced technology have significantly reduced the power and weight of proposed systems.)

The study made several important conclusions and recommendations, which were briefed at the fall 1995 CORONA Conference. First, the team concluded that a better understanding of the sensing requirement

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[17] Industry Briefing, 24 June 1998, Johns Hopkins Applied Physics Laboratory. Documentation is available from DJPO.

[18] Available from SMC/XR. A summary is available at http://www.afbmd.laafb.af.mil/xrt/sensor/index.htm.

of a space-based system was needed. The team recommended that current users and future operators of an SBR system experiment with developers that are supplying simulated systems in realistic environments. A better understanding of the requirement, further detailed studies of alternatives, and demonstrations to manage risks would lead to an informed decision on when a space-based sensor system would become both technically and economically practical. The study team also observed that the commercial market influence on the space industry is rapidly and fundamentally changing the scale and timing of space enterprise. The study team concluded that the events of the 1995–2000 time frame, if supported by DoD work to understand the problem better, develop spacelift capability, and advance critical technologies, should provide a reasonable basis for predicting the era of practical tactical surveillance from space.

2.7.2 AFSPC/ACC SBR MTI CONOPS and Roadmap Documents

The AFSPC/ACC SBR MTI CONOPS[19] was developed and published in 1997–1998. The CONOPS calls for initially fielding an SBR constellation as an augmenting system (versus replacement) for current MTI assets. A key point of this CONOPS is that it calls for AFSPC to control the constellation through a centralized payload control center (PCC), with primary tasking from the Joint Air Operations Center. The theater commander would normally task the constellation, through the PCC versus directly to individual satellites. In very rare cases, the CONOPS allows for a direct tasking of a satellite from the theater, but it is clear that this is meant to be an exception to normal operations. The CONOPS envisions that the normal control through the PCC could occur in near real time. The CONOPS calls for data distribution to be performed in the “most expeditious manner,” with capability to downlink data directly to theater or aircraft, as well as capability to link data back to CONUS.

The SBR MTI Roadmap Document[20] is a companion to the SBR MTI CONOPS document, and provides a roadmap for SBR development assuming an SBR system that is used in the manner described in the CONOPS document, with initial operational capability (IOC) in the 2010 time frame.

2.7.3 SMC/ESC Platform Independent MTI Study

The SMC/ESC Platform Independent MTI Study[21] was initiated in 1998 and focused on command, control, and communications architectures for SAR and MTI systems. Because there are increasing numbers of platforms for collecting MTI and SAR data, this study looked at developing a common architecture for passing data and tasking systems to collect data. The goal of the study was to develop a tasking and data distribution system that would be independent of the sensors and taskers. An initial conclusion of this study is that a protocol for passing GMTI data is needed so that systems that are currently being developed, as well as existing systems that are being upgraded, can be designed to provide data according to the accepted protocol. The actual protocol has not yet been determined, and the study is ongoing.

2.7.4 Office of the Assistant Secretary of Defense MTI Requirements Analysis Study

The MRAAS study was directed by the OASD, on behalf of the Joint Staff, in 1997.[22] The study’s goal was to determine what MTI sensing functions should be performed from the various MTI platforms, including ground, air, UAV, and space. The study suggested that the appropriate GMTI from space would be a deep look in theater, as well as periodic looks in areas where JointSTARS is not deployed.

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[19] Available from AFSPC, AFSPC/DO, 150 Vandenberg St., Suite 1105, Peterson AFB CO 80914, (719) 554-3100.
[20] Ibid.
[21] Available from SMC/XR.
[22] Available from OASD/C^{3}ISR.

2.7.5 AFSPC/ACC Concept Development Group

The Concept Development Group was established in response to an Air Staff tasking to determine and verify what requirements and capabilities should be displayed by the Discoverer II demonstration program. Led by AFSPC and ACC, the group has membership in all the Services. The group met over a period of several months in 1998 and published a draft document outlining proposed requirements and capabilities.[23] The effort is ongoing.

2.7.6 SMC Surveillance and Threat Warning (S&TW) Technical Planning Integrated Product Team

The SMC S&TW IPT develops concepts for systems to solve AFSPC deficiencies (for example, the inability to track airborne targets on a 24-hour basis independent of weather). The IPT publishes these concepts in the S&TW Development Plan.[24] The 1997 development plan contained six SBR concepts for meeting AFSPC deficiencies.

2.7.7 AFRL SBR Integrated Product Team

In 1996, SMC commissioned the AFRL SBR to develop answers to questions posed by the 1995 CORONA, to develop potential concepts for SBR systems (including SAR, GMTI, and AMTI), and to identify and research critical technologies.[25] The IPT has become a large group of experts in various SBR areas, such as antennas, power systems, signal processing, modeling and simulation, and systems engineering. The principal design developed by the IPT is the SPEAR, which represents potential objective system design, but *not* the precise system that might be fielded. In addition, to SPEAR, the IPT has developed other concepts, including bistatic and novel small satellite concepts. The IPT has developed representative technology roadmaps, which show the necessary technology advances needed through the 2003–2005 time frame for fielding a SPEAR-like SBR system. Most of these technology advances would be useful to any eventual SBR. The IPT is currently evolving the SPEAR design through modeling and simulation efforts.

2.7.8 Discoverer II

Discoverer II is a joint (DARPA, Air Force, NRO) technology demonstration effort that will be used to demonstrate GMTI and SAR capability from a single satellite. The demonstration will consist of two satellites with several GMTI and SAR modes. Although the Discoverer II program is strictly a two-satellite technology demonstration effort, it is anticipated that it will lend insight into the eventual development of a larger, more capable GMTI/SAR constellation. One goal of the program is to provide a conceptual design for a future constellation. As such, the program hopes to demonstrate technologies that may be key in a follow-on system. As technologies and system CONOPS continue to develop and evolve, it is possible that the follow-on system to Discoverer II may be virtually the same as or significantly different from the demo itself. The program schedule calls for launches in 2003 and 2004, with on-orbit operation and testing through 2005. The results of this demonstration effort, coupled with further work on requirements and CONOPS, will provide input to the eventual design of an operational GMTI/SAR constellation.

2.7.9 Modeling and Simulation Efforts

Multiple modeling and simulation efforts are being pursued by AFRL, SMC, and NRO. These efforts include technical capability models and military utility simulations (with and without man-in-the-loop

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[23] AFSPC/DO.

[24] SMC/XR.

[25] AFRL/VSSS.

capabilities). Details are available from the responsible offices.[26] A few commercial programs also exist; however, none currently addresses all issues related to SBR.

2.7.10 Individual Architecture Studies

Several individual concept designs have been developed and briefed. These designs are available in the S&TW Development Plan. Table G-2 gives a sampling of point designs and concepts that have been briefed at high levels.[27]

Table G-2. *Point Design Concepts*

Program	***Briefed To***	***Functions***
Passive Bistatic	DeKok, Dickman, Moore, Lyles, Israel, Larned, Tilelli, Libutti	AMTI
SPEAR	Estes, DeKok	GMTI, AMTI, SAR
MIT	Muellner	AMTI
1995 Space Sensor Study	1995, 1997 Corona	AMTI, GMTI
Starlight/Discoverer II	Ward, King (USA), Dantone (USN)	SAR, GMTI
ESC Bistatic	Gordon, Nagy, Vicellio, DeKok, Dickman	AMTI, GMTI

2.8 Conclusions and Recommendations

SBR is receiving strong consideration as a potential sensor platform for collecting SAR and GMTI data, as evidenced by the many ongoing SBR efforts, studies, briefings, and demonstrations outlined in the previous section. Technology advances in recent years have made SBR a viable option in the near term. The Air Force Scientific Advisory Board (SAB) Payloads Panel makes the following observations and recommendations with regard to the development and fielding of an SBR system.

2.8.1 SBR Provides a Significant Step Toward Global Awareness

Even with small constellations of perhaps five to seven satellites, SBR can significantly contribute to global awareness by providing periodic deep looks within a theater, initial in-theater looks prior to operational deployment of JointSTARS, and periodic looks in regions where JointSTARS is not deployed or cannot fly. The concept of an augmenting SBR system (at least in the near term) for providing MTI data has been endorsed at high levels. Additionally, cost will likely drive an initial SBR system to be an augmenting system (of a small number of satellites) to existing GMTI assets.

2.8.2 SBR Must Operate in a System-of-Systems Architecture

To augment existing systems, an SBR system must be designed to function in a SOSA. This architecture has not yet been defined, although initial steps have begun. Significant work remains in determining how individual sensor platforms will integrate into the SOSA. This work should proceed as quickly as possible. Of particular importance is the development of protocols for data communications and information passing. Although initial SBR systems will likely be small in terms of the number of satellites, it is prudent to design individual satellites so that evolving to a larger constellation is practical. This will allow for phased increases in SBR capacity. Ideally, the SBR constellation will evolve beyond GMTI and SAR capacity. As technology improves and as satellites are added to the SBR constellation (either through attrition or to increase constellation size), other capabilities should be added, such as

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[26] AFRL/VSSS and SMC/XR. The NRO point of contact is available from SMC/XR.
[27] SMC briefing to the 1997 Senior Leadership Forum, available from SMC/XR.

AMTI and CONUS wide area surveillance (WAS). Careful, up-front planning will allow the designing of a short- to mid-term GMTI and SAR constellation that will be more readily expandable to future (long-term) AMTI and WAS capability.

2.8.3 Any SBR Design Must Consider Overall Life-Cycle Costs in Addition to Individual Satellite On-Orbit Costs

Current emphasis in SBR design is on per-satellite cost. While this is a starting point for system costing, other factors must be included in cost estimates: launch costs, staffing costs, ground infrastructure costs, and replenishment costs as satellites approach end of life. A system with low per-satellite costs may be more expensive than a system with higher per-satellite costs, owing to a need for fewer higher-priced (but more-capable) satellites, differences in satellite lifetimes, or infrastructure requirements. The overall life-cycle cost issue should be carefully investigated prior to commitment to a satellite design for an operational SBR system. Additionally, cost avoidance issues should be studied in terms of the savings possible if the AWACS or JointSTARS fleet can be reduced. According to the AWACS Requirements Roadmap, signed by HQ ACC/DRC, 16 May 1996, "Approximately 140 very high value Command, Control, Communications, and Intelligence (C^3I) and standoff electronic warfare platforms will require replacement between 2007 and 2025. At an estimated replacement cost of *half a billion dollars a copy*, it does not appear to be cost effective to replace the B-707, C-130, and P-3 families of C^3I platforms through individual replacement programs."

2.8.4 A Centralized Office of Primary Responsibility (OPR) for SBR Is Needed Now

As the number of programs listed in the previous section indicates, many organizations are active in SBR efforts and studies. The Discoverer II demonstration effort is perhaps the most important program under way, and it provides several insights into the way an SBR system should be designed.

Subsequent to the demonstration effort, the Air Force will probably lead a follow-on effort to design, build, and field an operational SBR system. The Air Force must begin now to focus the many potentially overlapping studies, simulation efforts, and CONOPS development efforts. While Discoverer II will provide a short-term demonstration, the Air Force must develop the final design of a full GMTI and SAR operational constellation. The Air Force should set up an OPR very soon to begin planning for the follow-on effort to Discoverer II. It takes a minimum of 5 to 7 years to receive frequency allocations for satellite systems, and the Federal Government is actively selling frequencies. If the Air Force waits until the conclusion of the Discoverer II demonstration to begin the frequency allocation process, it is highly likely that the follow-on effort will incur significant delays, and frequency spectrum will be difficult to obtain—especially for wide-bandwidth (600 megahertz [MHz]) designs such as those proposed for Discoverer II. An OPR, if established very soon, could begin now to resolve long-lead-time issues.

Additionally, since Discoverer II is a very near-term effort, the program will not have a primary focus on developing technologies needed for the follow-on system. An OPR could provide that focus. The OPR for the follow-on system could be at any of several organizations. Historically, SMC has been the OPR for space systems, such as the Global Positioning System (GPS) and SBIRS. Another potential OPR would be AFSPC. A strong candidate for co-leading the OPR would be NRO, since national systems will likely have overlapping requirements with Air Force systems. Finally, it is anticipated that the SBR IPT at AFRL will be a key contributor to the OPR, with a focus on technology development for the follow-on system to Discoverer II.

Once an OPR is established, the following key steps should be taken in the procurement of an operational SBR system.

2.8.5 Proposed Steps Toward the Logical Development of an Operational SBR System

- Determine and appoint the OPR for Air Force SBR development efforts.
- Establish an accepted draft CONOPS for SBR systems in the 2010 and 2025 time frame as part of an overall SOSA. This could be based on the AFSPC/ACC SBR CONOPS document, the MRAAS, or some other document or study.
- Using an accepted draft CONOPS, develop and evaluate draft system architectures, based on capability, life-cycle cost, risk, interoperability with other DoD and coalition systems, and migration potential from a 2010 architecture to a 2025 architecture.
- Modify the draft CONOPS and architecture based on lessons learned from modeling and simulation, wargaming, and the Discovery II demonstration program.
- Field an initial system of "n" satellites. This may be an incremental process in which increasing capabilities are realized as additional satellites are launched.
- Evolve CONOPS and architecture for a 2025 system.

3.0 Communications

3.1 Summary

The key findings of this panel are as follows:

1. Commercial satellites will play a significant role in satisfying future military communications needs. They have the potential for cost savings and timely increases in capacity, while benefiting from the commercial investment, broad set of user services, and growing capabilities. At the same time, a military infrastructure needs to be preserved to address survivability, jamming protection, and hot-spot capacity requirements.
2. Technologies to support advanced SATCOM networks (LEO, MEO, and GEO) are well along in development (should be available in the 2000–2005) time frame and continue to evolve, driven to a significant degree by commercial market opportunities. These include wide-scanning, low-sidelobe, multibeam, uplink, and downlink antennas with active arrays; on-board processing switches capable of digital beamforming, large bandwidth, and power and frequency control; and RF/laser cross-link communications. These will lead to space-based ethernet architectures where LEO and MEO constellations support routing and server functions and GEO constellations support broadband, broadcast, and multicast services.
3. Future military space architectures will require movement of significant quantities of sensor-derived data from ground, airborne and space-based sensors to theater command centers and CONUS-based processing centers, and redistribution of processed data to end users with guaranteed delivery to multiple addressees. The Air Force should develop a military space-based-ethernet architecture that utilizes commercial capabilities and augments them, where needed, with commercial buses carrying military networking payloads and standard laser cross-links. Plans for development should include early experiments to validate sensor data dissemination to theater and CONUS via cross-links to planned commercial satellite networks, such as Teledesic or Spaceway.
4. Spectrum demands will continue to grow. The Air Force needs to be proactive in protecting its needs, while taking advantage of commercial systems. L-band demands will be particularly severe. The

GPS spectrum offers the possibility of supporting limited narrowband communications in addition to navigation functions. Increasing bandwidth needs will lead to increased Ka-band and V-band applications, especially for next-generation bandwidth-on-demand systems.

3.2 Introduction

Military communications needs are growing while budgets continue to shrink. Commercial communications systems capabilities are growing at an explosive pace, offering ever-growing capabilities. For many military applications, commercial systems offer viable military solutions, while other applications such as those requiring assured access, coverage in all areas (when needed), survivability, surge hot-spot capacity, and security require military-unique solutions.

Military communications can benefit from commercial communications developments in two different ways: through the direct use of commercial systems to satisfy military needs and by applying commercial technologies and interface standards to the development of dedicated military systems. In addition to lower capital costs, commonality with commercial systems affords the military the ability to leverage the commercial technology investment base in ground equipment, software, terminals, and system features. To achieve this, it is important to carefully review investments in legacy systems and infrastructure (e.g., terminals) to ensure that acquired systems can evolve as commercial technology evolves.

The future military satellite communications (MILSATCOM) architecture addresses three types of communications services: mobile services, wideband services, and protected and survivable services. All three must be brought to bear in an integrated fashion in order to achieve the objectives of *Joint Vision 2010*. To address these needs, future communications systems will utilize mixes of LEO, MEO, and GEO constellations, both commercial and military. Each constellation type offers benefits to a total architecture solution, with LEO and MEO satellites offering benefits in good coverage and low latency, and GEO satellites offering benefits in capacity, regional coverage, and survivability.

Technologies to support advanced SATCOM networks (LEO, MEO, and GEO) are well along in their development and continuing to evolve. These will be available in the 2000 time frame and will continue to evolve in support of 2005–2010 needs. These will lead to architectures similar to local area networks, where LEOs and MEOs act as servers and routers for mobile and fixed narrowband and mediumband communications, while GEO constellations support wideband, broadcast, and multicast services.

The explosive growth of commercial communications has fueled an unparalleled demand for spectrum resources. Military access to spectrum is under attack or being curtailed. Criteria such as efficient use of spectrum will become a dominant factor in future spectrum allocations. The Air Force needs to leverage commercial capabilities in L- and Ka-band, and leverage and support commercial moves to V-band. In addition, it needs to actively monitor and participate in spectrum activities to protect its needs. Finally, it needs to give consideration to user terminals combining mobile communications and navigation functions (which commercial industry is already pursuing).

A Defense Information Systems Agency (DISA) assessment shows an estimated combined military communications requirement of about 40 Gbps by 2010. About half of this requirement is addressed by ground communications, with the other half addressed through space-based systems. As shown in Figure G-4, an estimated 17.1-Gbps capacity can be addressed only through space-based systems. Specific requirements estimates for various types of communications are also shown in Figure G-4. The 17.1-Gbps capacity is evenly divided into three types of uses: (1) infrastructure (Defense Switched Network backbone, intelligence agencies, indications and warning, and strategic applications); (2) daily military operations (training, current crisis, maritime patrols); and (3) crisis response (deployed and in-transit forces, tactical and reachback, UAVs, etc.).

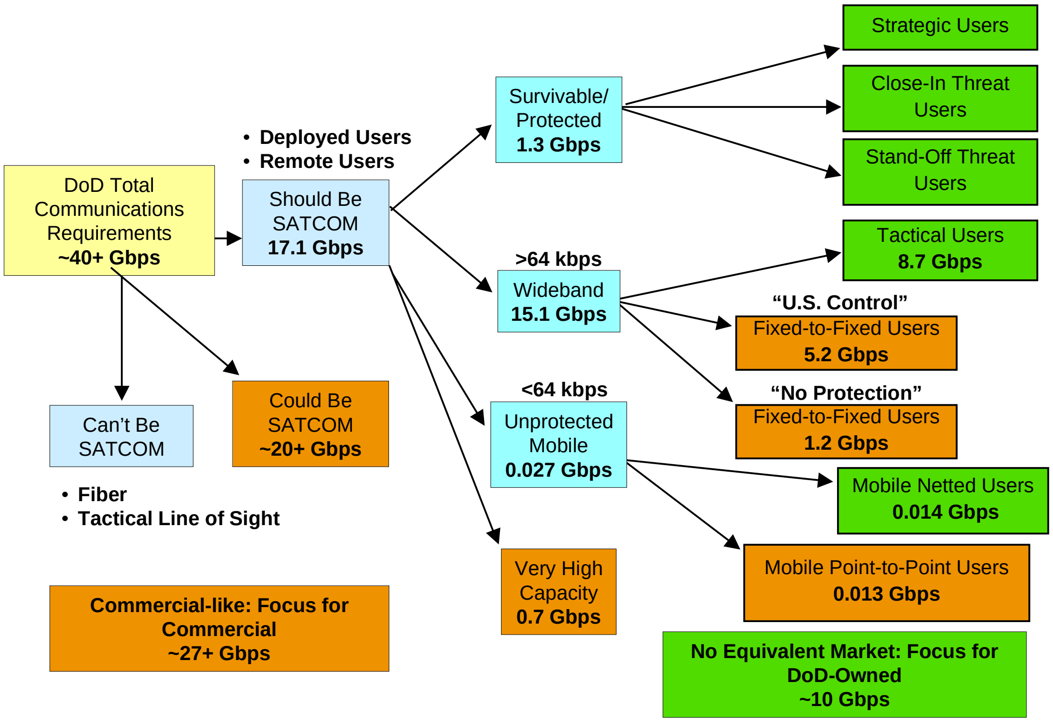

Figure G-4. *DISA Forecast of DoD Communications Requirements for 2010*

Figure G-5 shows DISA's assessment of the projected infrastructure wideband communications capabilities versus projected needs. It depicts a significant gap that will develop in the next 10 years. This could be partially offset by the use of commercial systems.

Commercial space systems wideband capacity (C-, Ku-, and Ka-band) is expected to more than double in the next 10 years. It is currently at about 4,500 transponders (equivalent to 36 MHz) and is expected to grow to about 11,000 by 2007.[28] This represents a potential future capacity of 800 to 1,600 Gbps.

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[28] "World Satellite Communications and Broadcasting Markets Survey—Prospects to 2007," Euroconsult, 1998.

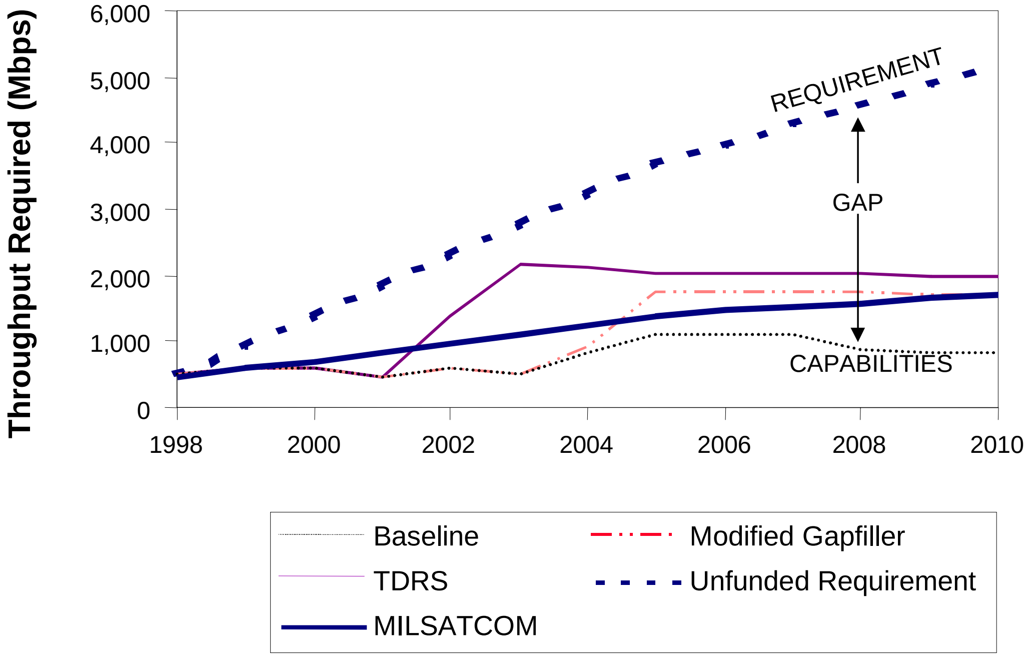

Figure G-5. *DISA Forecast for Wideband Communications*

Expanded discussions on the findings in this section are presented below. We begin by discussing commercial communications issues and trends, followed by the status and future of military communications: wideband, narrowband, and protected and survivable. Next we discuss an advanced concept for the development of a space-based ethernet to support military dissemination needs while utilizing advanced commercial capabilities. Finally, we discuss issues and trends associated with critical enabling technologies: antennas, processors, and laser communications.

3.3 General Trends in Communications Satellites

Commercial SATCOM is experiencing unparalleled growth due to global market demands, while funding constraints have limited the government’s investment in new government-unique systems. This broad economic base for commercial communications applications is leading to ever-increasing capabilities and services being offered by commercial providers. Consequently, government users need to consider how these emerging and planned commercial SATCOM systems can augment or supplant some of the dedicated SATCOM systems that they now operate.

As discussed in this section, commercial satellite systems have clear benefits for military users and will have an increasing role to play as they evolve. At the same time, commercial systems cannot handle all military requirements and must be carefully evaluated when used as part of a total architecture concept to enhance MILSATCOM needs.

3.3.1 Military Communications Requirements

The Capstone and Functional Requirements Documents for satellite-based communications list seven primary categories of military requirements: coverage, protection, capacity, interoperability, access and control, quality of service, and flexibility. Affordability is a separate issue of extreme importance.

Commercial SATCOM systems satisfy these requirements to varying degrees. They score well where military and commercial requirements are similar, but poorly where these requirements are dissimilar. Military requirements not well satisfied by commercial satellite systems include capacity in regions with high information density (hot spots), protection for jammers other than nuisance jammers, assured access, coverage in areas with low commercial economic benefit, and affordable transition of terminals and ground infrastructure.

3.3.1.1 Capacity

Existing military satellites lack sufficient capacity to meet current requirements, which does not bode well for their support of future requirements for much increased capacity. Planned and emerging commercial SATCOM systems provide large capacities that seem better matched to future military requirements. But raw capacity alone is not sufficient because military users tend to cluster in relatively small regions characterized by extremely high throughput rates that exceed the capacity that a commercial system can bring to bear in a small area.

3.3.1.2 Jamming Protection

Commercial satellite systems provide neither highly protected services nor services protected against other than nuisance jamming. They offer no antiscintillation, no low probability of intercept (LPI)/low probability of detection (LPD), no nuclear survivability, and no resistance to high-altitude electromagnetic pulses. To provide protected service against nuisance jamming, which represents less than one tenth of protected requirements, broadband traffic must use an antijam modem such as the Universal Modem. Satellite-based mobile systems that employ code-division multiple access can also defeat nuisance jammers but at the cost of much-diminished capacity.

3.3.1.3 Assured Access

Commercial providers control their own space assets and may depend on a ground infrastructure that is partially owned and operated by foreigners. Some systems are owned by foreign companies or international consortia that do not have the same objectives as the U.S. military. In addition, obtaining host nation approval to operate DoD terminals worldwide can take a long time.

3.3.1.4 Affordability

Affordability is critical for all military systems, including SATCOM. For commercial systems, limited compatibility with existing military terminal populations results in a need to replace most of this inventory through a lengthy and costly transition period. Adoption of a new terminal population raises serious concerns about the investment necessary to procure, install, and integrate these terminals. Hence, transition to commercial systems requires well-laid-out plans that accommodate the evolution or replacement of the legacy systems.

3.3.2 Commercial Systems Characterizations

Current, emerging, and planned commercial communications satellites (COMSATs) and communications systems can be characterized as mobile, broadcast, and fixed service. They can also be characterized with respect to their own features, such as geographic coverage, capacity, data rates, and number of simultaneous circuits supported, and also by the availability of features desirable in military applications, such as jam resistance and netted conferences. These characterizations reveal four major findings.

First, systems offering innovative services are invariably developing satellites, terminals, and a ground (control) infrastructure as a coordinated whole. Consequently they neither draw upon nor benefit from legacy terminals and infrastructures, either commercial or military.

Second, advances in the supporting technologies for satellite, control, and terminal segments affect the three commercial services differently. New mobile voice services rely on advances in the use of a vocoder, error correction coding, and multiple access techniques to provide low data rate (LDR, not exceeding 9.6 kilobits per second [kbps]) service to handheld units anywhere, anytime by the turn of the century and as much as 64-kbps service in their second-generation systems. Mobile narrowband data services use more mundane technology because they intend to compete on cost alone.

Digital compression technology and high-power transponders are transforming broadcast services from a single channel per carrier with medium-size antennas to hundreds of channels per satellite using small antennas. Fixed services have already exploited digital technology and will continue to see evolutionary improvements in capacity and link availability. For fixed services, the advent of on-board processing is a revolutionary development that offers high bandwidth efficiency and T1 and partial T1 connectivity via ultrasmall-aperture terminals, thus eliminating tail circuits and complex multiplexers at the terminals.

Third, commercial SATCOM is familiar to DoD, which already uses commercial systems, including purchased items such as Inmarsat terminals operating at L-band, Challenge Athena terminals at C-band, and Trojan Spirit terminals operating at both C-band and Ka-band, as well as leased items such as the transponders procured under the Commercial Satellite Communications Initiative. In addition, DoD routinely experiments with emerging commercial systems to determine their applicability. The Phase I Global Broadcast System (GBS) makes use of an Orion Ku-band transponder and modified DirecTV hardware. Also, on a limited basis, forces in Bosnia are experimenting with the use of Omnitracs transmitters for tracking materiel movement. At present, however, DoD's largest use of commercial COMSATs remains its network of private transponders used to provide surge capacity in crisis situations.

Fourth, emerging commercial systems offer new features that may find military application where none is now available. For example, emerging mobile satellite systems offer messaging and paging service while fixed-service satellites with on-board processing provide multicasting.

3.3.3 Commercial System Trends

Currently, GEO satellites provide most SATCOM services. Figure G-6 shows the commercial COMSATs in geosynchronous orbit today. LEO satellites will soon offer both voice and data service, albeit at LDRs (between 4.8 and 9.6 kbps). At least four systems (Iridium, Globalstar, ICO, and Ellipso are candidates) offering narrowband voice services should be operating in 2005. Their next-generation upgrades (Iridium, Globalstar, and Ellipso have already applied for a Federal Communications Commission license for next-generation systems), supporting data rates at least one order of magnitude greater, should be operational by 2010. These upgrades are likely to offer competitive performance just like their predecessors. At least two systems offering only low-rate data services (Orbcomm, FAISat, E-Sat, and Leo One USA are candidates in development) should be operational in 2005, but they are likely to be supplanted by their upgraded cousins by 2010. Table G-3 shows key characteristics for representative narrowband commercial systems.

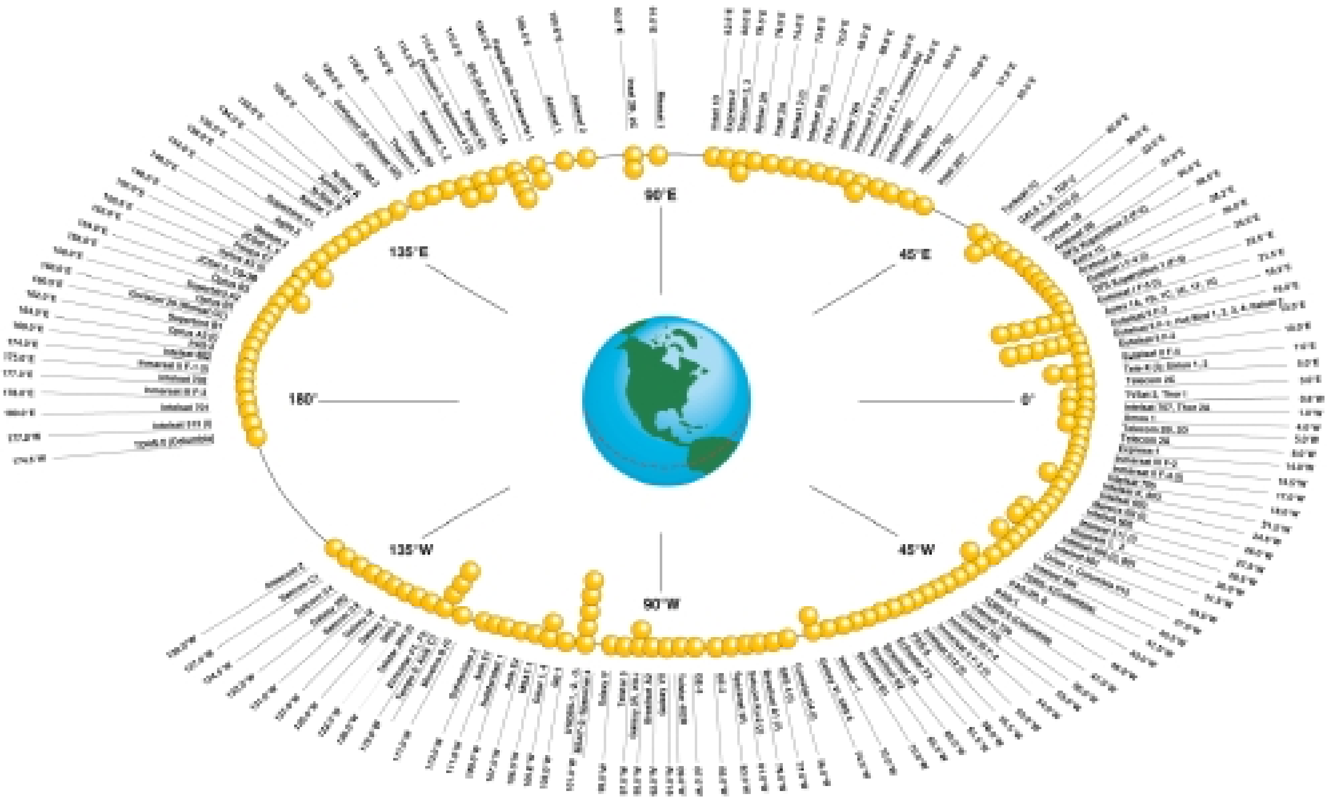

Figure G-6. *Commercial Communication Satellites in GEO*

In addition, by 2005 there should be two operational LEO broadband data (processing satellite) systems (Teledesic and Skybridge are under development, Celestri merged with Teledesic, and at least one other, Globalstar GS-40, has been proposed) that offer fixed users connectivity at T1 rates and multiples thereof. These systems are likely to be maintained through 2010, although significant upgrade of their capabilities is not expected by that time.

Table G-3. *Representative Narrowband (Voice Data) Commercial Systems (Planned/Under Development)*

	Iridium	***Globalstar***	***ICO***	***Ellipso***	***Regionals (Thuraya, APMT, ACeS)***
No. of Satellites	66/6 planes	48/8 planes	10/2 planes	6–24	1–2
Orbit	LEO	LEO	MEO	HEO/LEO	GEO
Coverage	Global	Global	Global	Global	Regional
Max Data Rates	4.8 kbps	9.6 kbps	4.8 kbps	4.8 kbps	4.8–9.6 kbps
Access Mode	Time Division Multiple Access (TDMA)/ Frequency Division Multiple Access (FDMA)	Frequency Division Multiplexing/Code Division Multiple Access (CDMA)	TDMA	FDMA/CDMA	FDMA/TDMA
Modulation	Differential QPSK	Quadrature Phase Shift Keying (QPSK)	QPSK	Offset QPSK	QPSK
Handset Frequencies	L-band	L-band	S-band	L-band	L-band
On-Board Processing	Yes	No	Yes	No	Yes
No. of Support Beams	48	16	163	8	160–250
Equivalent System Capacity (Voice Circuits)	3,200/Satellite	2,800/Satellite	4,500/Satellite	?	12,000–20,000
Dual Mode (w/Cellular)	Yes	Yes	Yes	?	Yes

Before 2005, there will also be one narrowband voice and data service operating in MEO (for example, ICO). This system will offer services that are competitive with its LEO counterparts. It is also expected to upgrade services by 2010 to remain competitive. In addition, four broadband data systems using MEO satellites (GSN, LM-MEO, Orblink, and WEST are candidates) have been proposed but more than one of these is unlikely to be operating by 2005.

During this period, GEO satellite capabilities will also show substantial improvement. In addition to routine upgrades of existing mobile, broadcast, and fixed-service satellites, multiple GEO systems supporting low-rate voice services and at least one that supports broadband data services (Spaceway, Cyberstar, and Astrolink are candidates) will appear before 2005 to challenge directly their LEO counterparts. Moreover, two (GSN and WEST) of the four broadband data systems using MEO satellites plan to supplement them with GEO satellites. Table G-4 shows key characteristics for representative broadband commercial systems.

Table G-4. *Representative Broadband Commercial Systems (Planned/Under Development)*

	Teledesic	***Spaceway***	***Voice Span***	***GE Star***
No. of Satellites	288	8 & 20	12	9
Orbit	LEO	8 LEO, 20 MEO	GEO	GEO
Coverage	Global	Global	Global	Global
Max Data Rates	16 kbps–64 Mbps	16 kbps–64 Mbps	32 kbps–2 Mbps	384 kbps
Terminal Frequencies	Ka-band	Ka-band	Ka-band	Ka-band
Capacity/Satellite	5 Gbps	4.4 Gbps	5.9 Gbps	1.8 Gbps
Beam Coverage per Satellite	576 cells	48 spot beams	32 spot beams	?

Narrowband voice systems (the LEO and MEO systems previously discussed, plus the regional GEO systems Thuraya, APMT, AceS, and Agrani) and broadband data systems are emerging or planned for all three earth orbits. Their similarities are remarkable. For narrowband voice satellite-based systems, each of them provides speaker-recognition-quality voice into a handset at 4.8 kbps. For broadband data, each provides multiple T1 data rates to a very-small-aperture terminal with relatively low transmit power.

Despite these similarities, these systems also have significant differences, including latency, coverage, required infrastructure, and service cost. LEO systems have a low latency compared to MEO systems, which, in turn, have a clear advantage over GEO systems. Moreover, GEO systems cannot offer full earth coverage (that is, high latitudes are omitted) and may be limited to regions, for example, no oceanic coverage. However, four GEO satellites can offer worldwide coverage (to 65° North and South latitude), whereas at least 10 MEO satellites and 48 LEO satellites are needed to provide global coverage; consequently GEO systems need less infrastructure and are likely to offer lower costs. Since none of them performs better when measured against all metrics, a user’s preference will depend on specific requirements.

3.3.4 Summary Recommendations on Commercial Systems

- Establish a clear strategy for use of commercial systems, taking into consideration future directions. Avoid “anchor investments” in the early stages of commercial developments until viability of new commercial ventures is established and prices become well defined.

- Assess commercial system applicability of unique military requirements. Consider alternative architectures, e.g., diversity of communications, use of fiber optics, and surge capacity.

- Develop plans for transition of legacy systems over time (especially ground systems and terminals) into commercial baselines to leverage on commercial investment and development for current and new applications (for example, paging and messaging).

- Ensure that commercial standards are followed wherever feasible to allow use and interoperability with commercial systems and to track commercial evolutionary paths.

3.4 Wideband Communications

The Advanced Wideband Service (AWS) consists of the Defense Satellite Communications System (DSCS)/ Service Life Enhancement Program, GBS payloads on ultrahigh frequency (UHF) and UHF

Follow-On (UFO), and new capabilities deployed on superhigh-frequency/Ka satellites, as well as the supporting ground infrastructure. That infrastructure is as important as the satellites. It provides for management and control of the entire network, as well as user transmit and receive terminals. There are two distinct classes of users for the AWS: tactical users who are highly mobile with smaller, less capable terminals, and infrastructure users who have stable locations and larger, more capable terminals, but individually have greater bandwidth demands.

Four principal issues concern the evolution of wideband capability: schedule, budget, scope, and commercial practices.

3.4.1 Schedule

DoD has planned a Gapfiller system for 2004 to bridge between current systems such as DSCS and the future objective capability, AWS, with a level of capacity significantly exceeding that available to the warfighter today. Adequate definition of the operational and functional requirements is needed to enable a successful commercial-like acquisition. While the Gapfiller focuses on tactical users, infrastructure users also need service. Tracking and Data Relay Satellite Systems (TDRSSs) I and J offer a unique early opportunity at a low incremental cost to provide an additional payload if an alternative launch vehicle is used.

DoD will field AWS after 2008. The capability that AWS is to provide remains to be determined by the results of operational use of the GBS now being implemented via the UFO (F8, F9, and F10) and by the actual development and performance of the Gapfiller constellation. Beyond that, evolution of commercial wideband systems such as Spaceway, Teledesic, and Astrolink will enable the Government to decide on the proper balance of government-owned and commercially provided capacity as well as the degree to which on-board processing should be incorporated in the architecture. In parallel, the evolution of control networks such as DSCS Operating Centers, terminals (such as future digital) and multimode terminals (such as the Ka enhancement of the Secure Mobile Anti-Jam Reliable Tactical Terminal) will play a crucial role in the definition of the actual service to be provided by AWS.

3.4.2 Budget

The budget allocated for the Gapfiller, as well as other elements of the MILSATCOM architecture, is constrained by the overall defense budget and depends on seeking as much capability as is affordable by maximizing the leverage obtained from commercial off-the-shelf (COTS) practices, components, and technologies. There is no money yet identified to address system management and control, which is essential to achieve the interoperability objectives of the program, nor for new Ka-band terminals.

3.4.3 Scope

As mentioned above, one question regarding scope of the Gapfiller is whether it will service the fixed infrastructure users as well as the mobile tactical users. This crucial question impacts the cost, complexity, and service availability of the Gapfiller. To the extent that the Gapfiller services both communities, it will be somewhat larger, it will require more power, and it will have a more complex operational concept and management. If growth of the Gapfiller is constrained for reasons such as budget, the use of the asset for infrastructure needs will detract from its ability to satisfy a sizeable portion of the tactical wideband requirements articulated in the Capstone Requirements Document (CRD) approved in April 1998.

A second aspect of scope concerns the need to address system management and control, as well as terminal compatibility, to ensure that the Gapfiller effectively operates in concert with the large legacy infrastructure that exists (or soon will) from the DSCS and GBS programs. The Gapfiller should leverage commercial standards to ensure compatibility and direct benefit from commercial system developments.

Furthermore, there is the question of how best to incorporate the new two-way Ka-band services, for which there is no legacy capability. We recommend that the telemetry tracking and control (TT&C) and payload control functions be included within the scope of the Gapfiller acquisition for the wideband service to operate successfully as an integration of capabilities from the DSCS, UFO/GBS, and Gapfiller systems.

3.4.4 Commercial Practices

The wideband program aims to maximize the use of commercial practices, technologies, and services. Commercial practices are readily in use in areas ranging from fixed-price contracts to purchase of parts. As noted earlier, firm and clearly defined requirements are necessary to successfully execute these commercial practices, or the risk of failing to procure the needed capability at the expected price will be high. The Government should avoid anchor investments in these early stages of commercial developments because of uncertainties as to the business viability of the new commercial SATCOM ventures, as well as the strong likelihood that competition will drive down the future price of these services.

3.4.5 Summary of Recommendations on Wideband Communications

- Use commercial solutions where feasible, and make the best use of commercial practices, components, and technologies in development of any unique systems.
- Resolve open issues concerning Gapfiller requirements for support of mobile tactical users.
- Consider incorporation of additional payload on TDRSSs I and J to provide early infrastructure capability.
- Address system management and control issues as well as terminal compatibility to ensure that the Gapfiller effectively operates in concert with the large legacy infrastructure that exists from DSCS and GBS.

3.5 Narrowband (Mobile) Communications

3.5.1 Current Military System

With the launch starting in 1993 of the current Navy-acquired UHF constellation of nine UHF satellites, DoD entered its fourth generation of narrowband SATCOM service. Gap analysis has shown that DoD must add at least one more satellite to prolong the life of the constellation of eight operational satellites beyond 2003 at greater than 70 percent availability.

The U.S. military has approximately 17,000 UHF narrowband terminals in the field, which have a sunken cost of approximately $7 billion. These communications conduits furnish approximately 70 percent of the communications used by our warfighters. Also, the recent evolving requirements database (ERDB) studies conducted in support of the Space Architect reveal that this system provides only 35 percent of the current demand for mobile (narrowband) military communications. These terminals provide eavesdrop, netted communications on the pause because their size and, in most cases, directional antennas require the operator to stop to set up communications links.

Demand assignment multiple access (DAMA) modems and more advanced waveforms, both of which will improve bandwidth utility, are in various stages of development and implementation. In the end, fielding such improvements in the ground terminals will cost hundreds of millions of dollars, and firm commitments to completely overhaul the infrastructure have not yet been made. When changes are made, the life cycle of this ground infrastructure will extend well beyond 2010.

3.5.2 Emerging Commercial Systems

Meanwhile, there is a revolution under way in regional and global handheld commercial communications systems. Iridium and Globalstar (LEO) and ICO (MEO) are global systems that will be operational between now and the turn of the century to extend the cellular urban systems to a worldwide market. Regionally, GEO systems such as Thuraya, APMT, and ACeS are well under way, leading to the provision of turnkey space-based telephony systems for underdeveloped countries.

The commercial market is very large in comparison to that of the U.S. military, and these systems have not, in general, been designed to support unique military needs. They feature many advanced capabilities that can benefit the warfighter: integrated communications and navigation; advanced functionality inherent in the cellular systems, such as netted radio, call waiting, and voice mail; and data rates of up to 9.6 kbps. On the other hand, they have limited link margins, usually impairing operations inside structures or under tree canopies, and lack interoperability between systems, leading to unique terminal requirements for each system. Usage fees for point-to-point communications will vary, depending upon system cost, but they are expected to be less than one half of the cost now incurred for use of Inmarsat satellite resources.

3.5.3 Advanced Military Narrowband System

The U.S. Government, through the Navy–led IPT in support of the Space Architect, determined in 1997 the priority characteristics for the narrowband system of the future:

1. assured access and control
2. eavesdrop, netted communications
3. handheld communications on the move
4. capacity consistent with the ERDB
5. interoperability with existing infrastructure and with our allies
6. protection

Of all the U.S. military communications services, narrowband is the least defined for the next generation, both in configuration and timing. This is because of the inherent motivation to utilize handheld COTS technology for simplicity as soon as it becomes available. However, the military is reluctant to commit to this sole course of action because of the need for assured access, the potential cost of a market fee for service, the lack of demonstration of other needed military characteristics to date, and the concern over the need to continue to support the current ground infrastructure well beyond the service life of the extended UFO satellite system. In addition, the Government fears that, in time of war, the U.S. military will be denied access to crucial narrowband pipes if the pipes are furnished solely by commercial (and particularly multinational consortia-led) systems. Furthermore, since all of the new “global” commercial handheld Mobile Satellite Systems (MSSs) are at either the L- or the S-band, there is a concern with regard to double-canopy rural and urban communications penetration limitations as compared to the current UHF system.

With only 35 percent of the narrowband demand currently satisfied, the Space Architect recommended several transition steps to mitigate this problem in the next 5 years, namely:

1. Provide for a continuation of the successful UFO satellite fleet through 2007, until the next-generation system can be determined and fielded.
2. Widely implement DAMA in the ground segment.
3. Utilize COTS MSS capability to provide fee-for-service surge capability.
4. Transfer traffic to wideband and protected pipes where feasible.

In order to address item 3, DISA, as a starting point, has contracted for implementation of an Iridium service gateway for the military in Hawaii, which will be operational in 1999. Work is well under way, sponsored by the National Security Agency, to determine standards for military protection for commercial handheld MSSs as well as to develop netted communications capability. Globalstar and ICO systems are also being worked in this area of satisfying military requirements. Few if any of these first-generation commercial systems will be able to meet the entire set of military requirements.

It is clear, however, that many of the technologies that are being developed commercially, such as the handheld terminals with security and the new standard ground switches, will be leveraged for direct application to the advanced narrowband system of the future, whatever it turns out to be.

The Navy, as acquisition agent for this service, has proposed to add an eleventh UFO satellite for a launch in the 2003 time frame. This will maintain a 70 percent service-availability capability until 2007, at which time the Navy proposes to field an advanced narrowband system. There is still some debate among the Joint Chiefs of Staff (JCS) as to whether this level of assuredness is adequate during this transitionary period.

The characteristics of the advanced system are being defined in time for the 2000 Senior Warfighting Forum process. The current guidance, as provided in the recently released MILSATCOM CRD, shows a military-owned UHF system with handheld, netted communications terminals. This system would be backward compatible with the existing narrowband ground infrastructure. The document also identifies the need for data rates for the next narrowband system to be at least 64 kbps in order to support personal computer- (PC-) based network-centric architectures of the future.

Spectrum availability is a crucial issue if there is to be an advanced narrowband military system. The UHF spectrum is being inefficiently used, and is under attack for potential sale to commercial interests. Furthermore, there are issues with its use for handheld terminals since their transmission limitations for user safety interfere with aggregate terrestrial use transmissions at the spacecraft. On the other hand, the more efficient, and therefore popular, L- or S-band frequencies have penetration problems and are consumed for other services worldwide.

3.5.4 Summary of Recommendations on Narrowband Communications

- Provide for continuation of the UFO fleet through 2007, until the next generation can be defined and fielded.
- Implement DAMA on the ground.
- Define narrowband requirements.
- Use COTS MSS capabilities for surge.

- Evaluate the future applicability of MSS. Develop a transition plan for legacy systems and evolution into an MSS-based system for commonality and leverage on commercial features. Work with commercial vendors to develop solutions for impaired terminal (e.g., tree canopy and structures) reception.

3.6 Protected and Survivable Communications

3.6.1 Today's Architecture

Extremely high frequency (EHF) SATCOM is ideally suited to missions where highly protected, highly survivable communications are needed. The first priority for these highly protected services belongs to the command and control of strategic forces through all levels of conflict up to all-out nuclear war. Some of the networks using these services are Emergency Action Message dissemination, force direction and report back, missile warning nets, and voice and data nets connecting the strategic Commanders in Chiefs with the National Command Authority.

With the deployment of the medium data rate (MDR) payload on Milstar DFS-3 through -6 (known as Milstar II) starting in 1999, protection can be extended to higher–data rate tactical services such as intelligence dissemination, air tasking orders, and beyond-line-of-sight communications between various elements of the tactical forces. Milstar II will provide greater worldwide capacity (maximum data rates of 1.541 Mbps versus 2.4 kbps on Milstar I and a cross-links capacity of 5 Mbps versus 128 kbps on Milstar I). Antijam protection for the higher data rates is maintained by narrow beam nulling antennas. Full JCS hardening ensures that the system will service and retain capabilities through all levels of electromagnetic pulse and scintillation attacks postulated in the threat assessment. Milstar DFS-3 is the first of a four-vehicle constellation providing both LDR and MDR worldwide communications in a fully cross-linked system.

The Milstar system is augmented by EHF packages (fully compatible with the Milstar waveform and interoperable with Milstar terminals) on vehicles 4 to 10 of the UFO SATCOM system. These packages provide additional LDR capacity on a spot basis where it is needed.

Further discussion can be found in the classified appendix.

3.6.2 Future EHF Architecture

Gap analyses for the Milstar space segment indicate that the probability of a healthy four-vehicle MDR constellation will drop below 70 percent in 2003, and the corresponding probability for a three-satellite constellation (the minimum number that can provide worldwide connectivity) will drop below 70 percent in 2006. To assure continuity of worldwide operations, the first launch of Advanced EHF (AEHF), the replacement for the Milstar system, is planned for 2006.

The AEHF effort is intended to offer considerable LDR and MDR capacity increases over Milstar while significantly reducing both satellite and launch vehicle costs. Bandwidth utilization, overall system capacity, and network reconfigurability will be greatly enhanced by the use of uplink DAMA, packet processing, and improved communications planning tools.

Data rates will increase by a factor of five to eight Mbps, while increased processing and downlink capacity will allow an order-of-magnitude improvement in total system throughput and a 30-times increase in the cross-link capacity. In addition, increased coverage, gain, and flexibility through the use of phased-array antennas will support increased capacity to more and smaller mobile-user terminals.

Although it is fully expected that LEO and MEO commercial communications systems will provide considerable capacity over the polar regions, none are expected to satisfy the crucial requirements for antijam and LPI/LPD. For this reason, as with Milstar, it is envisioned that AEHF will be augmented by continued use of hosted AEHF-compatible packages for polar coverage.

3.6.3 Transition to Future Architecture

Thousands of EHF ground terminals consisting of many unique types (Single Channel Anti-Jam Man-Portable Block I, Secure Mobile Anti-Jam Reliable Tactical Terminal, the Navy EHF SATCOM Program, etc.) will be fielded over the next several years. To benefit from the investment in these terminals, the AEHF system is being designed to be fully backward compatible with the current LDR and MDR waveforms. The new AEHF protocols, dubbed extended data rate (XDR), are being designed to support the new capacity requirements without interfering with the existing LDR-MDR terminals. In addition, the possibility of cross-banding between LDR-XDR and MDR-XDR protocols will ease the transition as older terminals can still communicate with the new terminals while awaiting retrofit or replacement.

A further consideration for future SATCOM is to avoid the stovepiping associated with present DoD architectures. Considerable effort is being applied to designing a system that will interface with the major DoD ground communication systems, such as the Worldwide Information Network (WIN), and the Defense Information Systems Network (DISN), and to assure that the AEHF system is integrated into the overall DoD communications architecture.

From the space perspective, AEHF satellite cross-links will be designed for backward compatibility with the Milstar system. Upon the initial AEHF launch, the new satellite can assume a position in the Milstar cross-link ring, assuring a continuity of worldwide communications. As the Milstar satellites are replaced, the new satellites can increase the cross-link throughput by a factor of 30—greatly increasing worldwide protected connectivity.

3.6.4 Special Considerations

By its very nature, the AEHF system requirements for survivability and protection drive the system and technology in different directions than the commercial world is headed. For this reason, early attention must be taken in the area of digital processing and efficient channel utilization.

3.6.4.1 Digital Processing Technology

Until recently, commercial COMSAT systems predominantly employed RF technology payloads, leaving only military COMSATs to develop space-based digital technology to support protected services. In recent years, however, space-based digital processing technology advancements have enabled new commercial COMSAT systems, which are now under development, to support thousands of simultaneous services. These commercial systems are in turn driving further advances in core digital technologies to reduce weight, power, cost, and time to market.

Commercial system design is driven by the high quantity of channels to be provided at low cost within the supporting satellite bus and launch vehicle. The technology focus is to reduce the required power and weight per channel through lower-power, higher-density integrated circuit devices, higher-density packaging, and customized designs to limit inefficiencies, which are compounded by the large number of channels.

These technology improvements for commercial systems support the government payloads as well, where weight and power reductions are also critical. However, the additional complexity for supplemental space-based resource control, higher-level protocols, flexibility over life, and complex waveforms (to provide antijam and scintillation protection) require additional technologies, including on-board processors and associated software, as well as other programmable and reconfigurable devices. Also important is the need for survivability in a nuclear weapons environment. Fully radiation-hard processor/device capability lags the commercial world capabilities by several years. Because of these complicating factors, early technology development efforts targeted to unique mission needs and survivability requirements are necessary. Especially important is the evaluation of system architectures designed for survivability using radiation-tolerant parts so that the features available to the warfighter do not significantly lag behind those available to the consumer.

3.6.4.2 Bandwidth/Channel Efficiency

The second special consideration for future EHF communications is in the area of bandwidth and channel efficiency. As the use of commercial communications becomes more widespread, additional ways are being found to use the available bandwidth more efficiently. Many of these methods, including frequency reuse, higher-order modulations, and closed-loop power balancing, are inherently more susceptible to jamming (intentional or unintentional) than the EHF missions can tolerate. For this reason, DAMA and packet processing architectures are likely to be highly used in the future EHF systems. These methods take advantage of the inherent “burstiness” of data communications to more efficiently route traffic. In addition, system use of packet processing can support data transport between EHF users and the rest of the community (for example, DISN connectivity). Early evaluation of these functions should be fully considered to ensure system efficiency and interoperability with DISN and commercial data transport.

3.6.5 Summary of Recommendations on Protected and Survivable Communications

- Incorporate commercial architectures for diversity.
- Design the system to integrate with the overall DoD communications architecture. Ensure that it interfaces with major DoD ground communications such as WIN and DISN.
- Evaluate the applicability of current commercial technology to meet survivability requirements.
- Evaluate the use of DAMA and packet processing architectures for system efficiency and interoperability.

3.7 DoD Space-Based Networks Using Commercial Satellites and Modified Commercial Buses

For many applications, DoD users will use commercial space-based networks to send and retrieve data. In fact, there are opportunities to use commercial services to fulfill operational requirements for data movement. However, there are militarily significant cases where commercial networks (as currently planned) will not support DoD user needs. In addition, it is unlikely that backward compatibility to military communications systems would be an economically attractive feature to include in commercial system designs.

See the for official use only appendix for examples of DoD unique needs.

We propose a mechanism to reduce DoD costs while taking advantage of commercial investments and providing advanced communications capabilities to military users.

The approach we offer will use commercial buses carrying standard laser cross-links (standard in the sense that the photons in space conform to an interface standard). We call these spacecraft ServerSATs, though in practice they can range from an enhanced commercial spacecraft carrying a laser cross-link receiver to a set of dedicated DoD-owned (but contractor-operated) spacecraft residing in and operated as an integral part of a commercial constellation.

ServerSATs are controlled by the same satellite control facilities and mechanisms that the commercial entity employs to control the other satellites in its constellation. ServerSATs communicate with each other and DoD satellites via cross-links (both laser and heritage RF), and inject traffic into the constellation owner's network.

ServerSATs might under some circumstances communicate directly with the ground, but more routinely would route data through their host constellation to a ground station, or where necessary relay traffic to the ground through dedicated downlink spacecraft.

ServerSATs can tie commercial communications links into military channels in a transparent way. A commander at a location outside of the theater might use a Secure Terminal Unit (Model III) (STU-III) to communicate to an in-theater user that has only a HAVE QUICK radio. This could be done by routing the STU-III output through a commercial digital satellite link as a serial bit stream and cross-linking it to a ServerSAT, where it would be converted from STU-III to HAVE QUICK format (and vice versa) and, after passing (potentially in multiple hops) through the ServerSAT constellation, be downlinked to a jam-resistant receiver on an airborne node (for example, airborne communications node) or at a ground station where the loop would be closed with the end user by transmitting (receiving) a HAVE QUICK waveform.

As the future communications architecture evolves, all future DoD satellites could be able to link into ServerSAT constellations. ServerSAT constellations would exist in LEO, MEO, and GEO, and would be able to cross-link from anywhere to anywhere with user-selectable channel bandwidth. Depending on the hardness of ServerSATs, their auxiliary payloads, and their ground stations, they could provide a significant amount of assured communications bandwidth even under stressing scenarios.

The most conservative implementation of a ServerSAT would consist of an additional laser cross-link on a commercial COMSAT (perhaps Teledesic or Spaceway) that would receive data from a DoD sensor satellite and inject them into the data stream of the constellation for routing and delivery directly to a DoD ground station. Should DoD decide that it needs a hardened version of a commercial bus, the development effort necessary to harden and verify the performance of the design, paid for by DoD, could provide additional protection for commercial users of the same bus.

Some issues must be resolved to make this concept fully acceptable. One issue is the level of radiation tolerance that ServerSATs will need.

If the basic commercial bus is tolerant of natural radiation levels only, is there any need or value to hardening the military payload to a higher level? On the assumption that commercial systems will not be hardened to higher levels, would it make sense to upgrade commercial buses to higher levels of radiation tolerance or to add other protective measures to those spacecraft that carry defense payloads?

We believe that the large redundancy of commercial satellites obviates hardening the satellite beyond levels adequate to protect it from natural phenomena.

If the notion of ServerSATs is adopted, then there are certain global changes that could take place in the architecture of space systems in general:

1. Sensor satellites could communicate through ServerSATs rather than needing dedicated communications links, possibly reducing spacecraft weight.
2. Full-bandwidth, continuous connectivity between sensors and ground processing centers would eliminate the need for on-board recorders and further reduce weight, cost, and data latency while increasing spacecraft reliability and life.

3. Standardization of requirements, and thus designs, for laser cross-links could cut the cost of individual payloads through reuse of both cross-link hardware and communications management software.

If commercial communications enterprises can be persuaded to carry standard laser cross-links in addition to those associated with their prime payload mission, to accept DoD traffic through both their normal gateways and the laser cross-links, and to route DoD messages through their system, then DoD could enjoy a wide mix of commercial communications services by paying commercial prices for incremental services. There is also a potential that through the process of defining a standard laser cross-link some degree of interoperability might be achieved between independently owned commercial constellations.

There are some interesting business aspects to this arrangement as well. If DoD became an early user of a commercial system and orbited its own ServerSATs after the commercial satellites were operational and DoD traffic had grown to a point justifying investment in a DoD-owned constellation, the commercial owners might enjoy a much more rapid rise in early revenue, with knowledge that when the DoD constellation became operational the DoD traffic would move off the commercial constellation as the planned commercial traffic growth was realized. The early revenue from this kind of arrangement might be enough to induce participation from otherwise reluctant commercial entities. Also, if the commercial constellation could route traffic through the DoD system during (DoD) off-peak periods, there might be a return of revenue to DoD should the commercial traffic grow beyond the initial estimates or more rapidly than anticipated.

3.8 Technology Considerations

3.8.1 Digital Signal Processor Technology Trends

Commercially oriented payloads based on digital signal processing have been driving several spacecraft technology areas since 1993. Commercial mobile telephony programs started the trend with the need for large amounts of flexibility and processed bandwidth. Next-generation regenerative wideband systems are currently driving core technology requirements in this area and will likely continue to do so. Capacity and flexibility demands are driving processed bandwidth (total bandwidth processed on board to meet program requirements) to staggering levels. This in turn is driving the need for sizeable power, mass, and cost improvements in order for commercially driven ventures to pay off. These pressures have led to an extraordinarily high level of innovation and technology advancement in commercial satellite payload, which in due course will undoubtedly migrate to the satellite bus and military payload sectors.

The flexibility afforded by digital beam forming greatly enhances the usefulness and revenue-generating capacity of spaceborne mobile telephony systems. Early systems such as Iridium and Globalstar have targeted modest capabilities. Systems such as ICO have achieved even more significant digital complementary metal on silicon (CMOS) and packaging technology advancements in order to reduce the power, mass, and cost to affordable levels. For example, through the application of low-voltage (2.5-V DC) CMOS and large (2- by 4-inch) multichip module packaging technologies in space, the ICO payload performs more than double the total operations per second performed on the entire array of Milstar II payloads (LDR, MDR, and cross-links combined). Radiation-hardened application-specific integrated circuits (ASICs) with 150,000 gates per chip have been achieved by multiple sources. These include 0.6-micrometer (µm) CMOS/Silicon on Sapphire, 0.5-µm CMOS on epitaxial deposition (epi), and 0.7-µm CMOS on silicon on insulator.

Regenerative wideband programs require further improvements: more power, and savings in mass and cost (for example, three to five times the current ICO capabilities). This large capability increase has led to the use of commercial deep submicron CMOS, which is consistently three generations ahead of conventional radiation-hardened CMOS. Commercial 0.25-µm CMOS on epi technology has already been qualified for space use with favorable results, and plans are afoot to qualify the new commercial developments in 0.18 µm CMOS. Given that most experts believe that Moore's law will continue to apply to this technology at least through 2010, one can expect 1999 capabilities of 12 million gates per chip at 400 MHz and 0.12 microwatts per gate-MHz to grow to about 1 gate per chip at 10 GHz and a few nanowatts per gate-MHz by 2010. Without any other major breakthroughs, no other technology will surpass CMOS as the workhorse in communications payloads in this time frame.

Given the phenomenal improvements in performance CMOS is making, the limiting factor on what can be accomplished on a spacecraft will become the cost of RF-to-digital conversion. Technology advancements in this area are not nearly as rapid as in the digital area because fewer investment dollars are available (that is, there is little commercial investment). The key here is to follow the analog technology evolution and apply system architecture improvements to significantly reduce the power, mass, and cost of this portion of the system. Emerging technologies, such as Silicon Germanium (SiGe) and Indium Phosphide (InP), are making it possible to realize monolithic intermediate frequency (IF) and RF bandpass sampling analog-to-digital converters (ADCs) and digital-to-analog converters. This trend will continue through 1999 and beyond to RF bandpass sampling at higher and higher frequencies. Direct conversion at Ku-band frequencies should be achievable in the next few years. Large power, mass, and cost savings will be achieved first through elimination of IF-to-baseband down/up converters and then through elimination of RF-to-IF down/up converters. SiGe will play an important role in these improvements because it offers very high usable bandwidth at low power, coupled with good high-complexity yield, enabling digital decimation in the same chip as the ADC. This promises the ability to enter a monolithic chip at RF and exit with digital data near Nyquist rates at the information bandwidth.

Several problems have arisen with the exploitation of deep submicron digital CMOS on satellites that will require continued investment and attention from the space community. First, manufacturers will need to work more closely with foundries and tool providers to be able to exploit the capability of these technologies, since the space applications are pushing the complexity and performance of state-of-the-art (SOA) commercial CMOS harder than that community's traditional customers. Second, although power per gate-MHz is dropping rapidly, the gate count per gate-MHz product is increasing more rapidly, meaning higher power per chip and the need for significant thermal impedance improvements. Technologies such as pyrolitic graphite heatsink technology (very near the thermal conductivity of diamond) offer potential to address this problem. Finally, advances in the SOA of interconnect technology (printed wiring boards [PWBs] and connectors) to accommodate the signal density increases will be required.

3.8.2 Summary of Recommendations on Digital Signal Processing

- Make use of capabilities offered by commercial suppliers. AFRL should monitor innovative approaches used by commercial manufacturers for potential incorporation into government systems.
- Develop closer working relationships among manufacturers, foundries, and tool suppliers to better exploit the capabilities of deep submicron ASIC technologies.
- Develop improved heat dissipation technologies to accommodate higher-density electronics.
- Develop improved interconnect technologies (PWB and connectors) to accommodate signal density increases.

3.8.3 Antennas

Significant breakthroughs in antenna technology in recent years have enabled the development of sophisticated mobile narrowband systems at LEO, MEO, and GEO. These designs support multibeam, low-sidelobe implementations. Many of these designs are scalable to support improved systems at MDRs and narrower beams. As we look ahead to the next-generation bandwidth-on-demand systems, additional antenna design improvements will be required.

3.8.3.1 LEO/GEO Networks

A number of technologies must be developed to support the concept of a data network. These technologies are expected to be developed in the next few years with launch in the 2003 time frame.

Wide-scanning, low-sidelobe multiple-beam uplink antennas capable of generating about 1,000 simultaneous beams must be developed. Steerable beams are desired to minimize network complexity, requiring low-cost, reliable monolithic microwave integrated circuit (MMIC) low-noise amplifiers (LNAs), phase shifters, and attenuators in large quantities (1,000 to 5,000 each per antenna). Dual polarization is required to maximize capacity through frequency reuse.

Second, wide-scanning, low-sidelobe phased-array downlink antennas capable of generating 20 to 30 simultaneous beams are needed. Rapid repointing of beams is required to support high burst rates to multiple users. As with the uplink antenna, large quantities of cheap MMIC power amplifiers (about 2,500 per antenna) and phase shifters (about 30,000 per antenna) will be required.

Development efforts that will support these implementations will include MMIC device cost reductions (solid-state power amplifiers [SSPAs], LNAs, phase shifters, attenuators, etc.) by two orders of magnitude; indium-phosphide MMICs to reduce power consumption; flip-chip packaging of MMIC devices to reduce chip size; low-loss, multilayer boards for RF signal distribution; and development of micro-electromechanical (MEM) switches and devices.

3.8.3.2 GEO Networks

From geostationary orbit, the trend as we approach 2010 will be toward increased capacity via smaller beam sizes, higher frequencies, coverage flexibility, and more-capable digital processing. This will require development of larger reflector and array antennas.

Larger reflector antennas with improved surface tolerances will be required to generate smaller beam sizes and higher frequencies. Several designs that exist today are readily scalable in size, but improvements in surface tolerance must occur to allow use at higher frequencies. Lighter-weight materials and more thermally stable materials will also be needed. As frequencies increase, array antennas become more viable. Lightweight, cheap radiating elements of two to three wavelengths in diameter, plus cheaper, more efficient SSPAs, LNAs, and phase shifters will be key areas for development.

3.8.3.3 Summary of Recommendations on Antennas

- Conduct research and development (R&D) to reduce the cost of MMIC devices (SSPAs, LNAs, phase shifters, and attenuators) by two orders of magnitude. Develop reduced-power MMICs (for example, indium phosphide).
- Improve packaging and interconnect methods.
- Improve RF signal distribution techniques, for example, low-loss multilayer boards.
- Continue development of MEM switches and devices.
- Develop large reflector, lightweight antennas with improved surface tolerances.

- Develop multibeam antennas and power amplifiers for V-band.
- Develop lightweight, inexpensive radiating elements for phased-array antennas at Ka- and V-band.

3.8.4 Laser Communications

Major breakthroughs in lightwave technologies in the past 10 years have led to reliable laser communication systems with very high performance. Their small size, light weight, high efficiency, extremely wide bandwidth and high immunity to interference and noise make laser communication systems far more attractive than RF systems for intersatellite link and, potentially, satellite-to-ground applications. The most simplistic argument for laser communications against RF links can be made by examining the antenna size: RF systems typically require 8-foot-diameter antennas, whereas optical telescopes tend to be less than 1 foot in diameter, making optical telescopes much more desirable for implementation on satellites.

Laser communications, on the other hand, need a cloud-free line-of-sight (CFLOS) beam path, which is an impediment to their widespread implementation for satellite-to-ground communications. RF thus may remain the choice for downlink systems. This problem, however, may be solved with research in diode lasers emitting at wavelengths less sensitive to optical loss due to clouds or atmospheric aberration.

In the following subsections, we discuss separately the two types of laser communications—satellite-to-satellite and satellite-to-ground—and conclude with some recommendations.

3.8.4.1 Satellite Cross-Link Communications

Historically, laser communications started as 850-nanometer (nm) systems. Current industry development efforts include 850-nm direct (noncoherent) detection, 1.06-µm coherent detection, 1.55-µm direct detection, and, most recently, 980-nm direct detection systems. All lasers mentioned above are diode lasers, except for the 1.06-µm lasers, which are typically diode-pumped solid-state lasers modulated by lithium niobate external modulators.

Two laser cross-links that are currently being developed are described here as examples. For a LEO-LEO cross-link at a 6,000-kilometer (km) orbiting distance, a 1-W, 2.5-Gbps laser at 870 nm is used with 15-cm diameter transmitting and receiving antennas. For a LEO-GEO cross-link (40,000 km), a 3-W, 5-Gbps laser at 1.55 µm is being developed with a 30-cm telescope. The minimum required laser power linearly depends on laser modulation bandwidth and quadratically depends on link distance over aperture size. The most important future goals for laser cross-links are increased bandwidth and reduced cost—both require higher-power lasers with high bandwidth.

Method to Increase Power

The power to be increased is large-signal modulated power and not continuous wave (CW) power. Hence, the most credible method is via the implementation of an optical amplifier. The breakthrough in erbium-doped optical fiber amplifier (EDFA) technology has enabled 1.55 µm to emerge as the preferred wavelength for future systems. EDFAs have the potential to provide greater than 10 W of transmit power. They also enable very high-sensitivity, high-data-rate receivers using an optical amplifier as an LNA with a pin diode detector.

For lasers in wavelengths other than 1.55 µm, there are no suitable high-power optical amplifiers. There has been research on semiconductor diode amplifiers. However, until the major issues on noise performance and sensitivity to optical feedback are solved, diode amplifiers will not be suitable for SATCOM applications. Currently, commercially available 850-nm diode lasers have limited output powers for data rates greater than 1 Gbps. Similarly, there are no commercial 980-nm lasers at high data rates. Much of this is due to the lack of research in high-speed, high-power diode lasers. Research in high-power, high-speed lasers at all wavelength regimes can lead to major advances in SATCOM and is highly recommended.

Researchers in the United States, Japan, and Europe have reported fiber-optic systems under development at data rates of up to 10 Gbps requiring about 1 W of optical output power from an EDFA. Data rates have the potential to go even higher—amplifiers have been reported with output powers in excess of 9 W. It is anticipated that these output power levels could get as high as 20 W in the next 5 to 10 years.

Method to Increase Bandwidth

The most cost-effective method to increase bandwidth is the dense wavelength division multiplexing (DWDM) system. DWDM technology has experienced explosive growth recently, primarily driven by the telecommunications industry. The demonstrated aggregate bandwidth is rapidly expanding into terabits per second (1,000 Gbps). DWDM systems deploy 1.5-μm laser transmitters emitting at different wavelengths at fixed spacing, typically 50 to 200 GHz, to yield an extremely high aggregate bandwidth. All transmitters are coupled into one physical fiber and amplified by the same chain of EDFAs. At the receiving end, the optical beam is demultiplexed by wavelengths and subsequently detected.

A brief calculation below illustrates the powerfulness of DWDM systems in expanding bandwidth. Typically, each diode laser transmitter is modulated at 2.5 or 10 Gbps (its CW line width of 100 kilohertz to 1 MHz is so narrow that it is considered a single-frequency source). The total aggregate bandwidth is the modulation bandwidth multiplied by the total number of channels, which in turn is limited by the EDFA gain bandwidth and the availability of wavelength division multiplexing transmitter and demultiplexing technologies. The SOA of commercial EDFA has a 30- to 35-nm (3 to 3.5 terahertz) gain bandwidth product. Recent announcements from the telecommunications industry indicated that two- and three-band EDFAs will become available with greater than 80-nm gain bandwidth product and 120-channel capacity. The aggregate bandwidth of a 120-channel system can easily be 300 Gbps, with each laser modulated at a moderate speed of 2.5 Gbps.

The fact that all the channels are transmitted through one physical fiber eliminates the need of adding transmission telescopes, a very desirable scenario for SATCOM. The power and environmental requirements are, however, very different for the two applications. As the number of channels n is increased, the power amplification per channel per EDFA is decreased by n. It is not clear whether cascading EDFAs can generate the power required for n channels of SATCOM, i.e., 3 to 10 times n W. In any case, it is clear that satellite cross-link applications will benefit greatly by leveraging the commercial DWDM development to result in a major cost reduction. We recommend research on DWDM components and systems to specifically address the power, lifetime, and environmental requirements for satellite applications.

New Capabilities Enabled by New Component Technology

The recent developments in wavelength-tunable diode lasers can lead to unprecedented new capabilities in communication systems. Researchers have demonstrated tuning ranges as high as 32 nm of continuous tuning and 140 nm of multistep discontinuous tuning. As the lasers typically have independent contacts for modulation and wavelength tuning, the emission wavelength and intensity modulation (IM) can be kept at any given relationship or be totally independent. Through the use of such lasers, dramatically increased security can be achieved by unique coding of wavelength modulation, phase modulation, and IM, or via the implementation of optical spread spectrum transmission. Another advantage for using such tunable lasers is increased signal-to-noise ratio (SNR) in communication links, which reduces the required optical power levels. Still another potential application is very high-resolution range detection (5-cm resolution at a distance of 500 km). Research and studies on such novel systems and applications as well as further development on wavelength-tunable devices are highly recommended.

Future Challenges

Laser communications have some challenges to overcome before they can be a standard building block of future satellite communication systems. The pump diodes required for the high-power EDFAs must be proven reliable enough to support the typical geospacecraft lifetime of 15 years. Diode life testing is under way to address this issue. The understanding of performance and design limitations of cascaded EDFAs is extremely important. Methods to increase the total output power for multichannel operation needs to be investigated.

Another challenge is radiation. Radiation darkens optical fiber, resulting in degraded output power for the optical amplifier. This effect can be minimized by reducing the length of the optical fiber. High-brightness diodes, such as phase-locked vertical cavity surface-emitting laser (VCSEL) arrays and surface-emitting distributed feedback laser designs, can result in significantly reduced fiber lengths. The high-brightness diode has the added benefit of increasing the amplifier efficiency and significantly lowering the power requirement for the laser communication terminal. Reliability of these devices has yet to be demonstrated.

3.8.4.2 Satellite-to-Ground Communications

See classified appendix for discussion of atmospheric distortion affects in satellite-to-ground communications.

3.8.4.3 Recommendations

We strongly recommend the following activities. Some of them are existing programs that require continued funding to sustain further development, whereas others are new programs that we recommend be initiated immediately.

- Conduct research in laser communication systems that have high tolerance toward attenuation and distortion from the clouds, dust, pollution, and other atmospheric substances.
- Conduct research and development in reliable, high-brightness diode lasers.
- Develop DWDM components that meet the power, lifetime, and environmental requirements for satellite applications.
- Develop wavelength-tunable lasers and their applications in optical spread spectrum communications, and combined wavelength, phase, and IM coding schemes.
- Characterize and understand atmospheric turbulence and the elimination of distortion effects on optical signals.
- Develop radiation-resistant laser communication systems.

4.0 Navigation, Position, and Timing

4.1 Introduction

Accurate navigation and timing are provided today by the GPS.

- GPS and system extensions being conceptualized by the GPS Independent Review Team (IRT) will satisfy both military and civilian needs when implemented.
- Improvements in precision timing enabled by incremental removal of error sources associated with the initial deployment of GPS promise revolutionary capabilities.

GPS was developed as a military system. It is being acquired by the Air Force and is operated by AFSPC to improve position accuracy for the U.S. armed forces. Provision was left for civil users, but the extent and need for accuracy by civil users was probably not foreseen by the original developers. A new civil industry developed that exploits the capability of GPS and must be recognized. This has put pressure on DoD to provide more accuracy and robustness for civil users. The advantage for DoD is that the large production runs for civil GPS receivers have reduced the cost immensely. The disadvantage is the possibility that enemy forces can be equipped at low cost with these civil receivers. In addition, what was envisioned as a military system has become exceedingly complicated, not only technically, but also politically.

Undoubtedly there are as many different opinions as there are authors about possible solutions for permitting civil users to employ the accuracy inherent in GPS while ensuring that U.S. and coalition armed forces can conduct combat operations in a nearby geographic area. Nevertheless, all authors agree that a solution or solutions must be found. (The author of this section is a member of the AFSPC IRT and was a member of a SAB Committee on GPS a number of years ago.)

This section presents a brief discussion of GPS with emphasis on the SAB Study recommendations for improving military capability while allowing civil users to continue to use GPS without undue interference from a nearby war zone.

4.2 References

Two excellent references provide detailed information on GPS: National Research Council, *The Global Positioning System, A Shared National Asset*, National Academy Press, 1995; and *The Global Positioning System, Assessing National Policies,* Rand Corporation, 1995.

4.3 Principles of Operation

The GPS constellation consists of 24 satellites (four each in six planes) in MEO at an altitude of 20,051 km with an inclination of 55°. The control station at Falcon Air Force Base (AFB), Colorado, maintains the ephemeris of these satellites and provides the position information to be broadcast by the satellites. The heart of GPS is timing. The satellites broadcast the time the transmission was made, and by noting the time of reception, the receiver can tell how far it is from the satellite. By quadrilateration the receiver can locate itself in latitude, longitude, and altitude. Assuming that all calculations have been made correctly and that there are no multipath reflections, there are three inherent errors in the system. The first is the time delay caused by the electromagnetic signal’s traversing the ionosphere. This can be corrected by having two frequencies transmitted and received. Since the delay is a function of frequency, the delay can be calculated. Timing inaccuracies cause the second error. The ground station and the satellites have cesium and rubidium clocks. At present this error is 20 nanoseconds or about 6 m, considerably less than that specified for military (16 m) and civil (100 m) applications. The basic secondary time standard maintained by the Naval Observatory at Falcon AFB is one picosecond (ps), based on a hydrogen maser. Various errors in timing introduced as the constellation was fielded can ultimately be eliminated. The limit may be about 100 ps or about 3 cm. The third error is in the ephemeris of satellites.

4.4 Codes, Frequencies, and Bandwidths

The discussion now becomes more complicated than it should be for a military system because of the civil applications. There are three codes: coarse acquisition (C/A), precision (P), and precision encrypted. The C/A code has a bandwidth of about 1 MHz and the P code about 10 MHz. Both employ pseudorandom-noise codes. Both codes are centered on a frequency of 1575.42 MHz, and the band is usually referred to as L1. The fact that both codes are centered on the same band creates a military problem because the C/A code assumed to be in the hands of the enemy must be denied by clever disruptive techniques or simply jammed in the area of the war zone. Both codes are broadcast by the satellites operating today. Civil users employ only the C/A code, but the military employs both. The military currently requires the C/A code to acquire the P code. This constitutes a second problem. Methods for the military to acquire the P code directly are being investigated.

A second set of codes is centered on a lower frequency of 1227.6 MHz, referred to as L2. Because of a lack of power, present satellites can broadcast only C/A or P on L2. A method for removing the C/A code from the center of L2 has been proposed by the IRT: placing the C/A code at the nulls of the P code in what amounts to double sideband modulation at about ±10 MHz from the center frequency of L2. That solves the military problem and provides civil users with three frequencies for ionosphere correction capability and more robustness of operation. A somewhat similar scheme at L1 would help the military jamming issue.

In addition, GPS has been designed to degrade civil accuracy by “dithering” the signal, a technique called selective availability (SA). The President of the United States has directed that SA be permanently discontinued by 2005. To avoid the errors introduced by SA, a series of ground stations has been introduced for averaging the signal for retransmission. This technique is called differential GPS. The ground stations do more than counteract SA; for example, they correct for the ionospheric delay better than a single receiver can do by an algorithm, and they also detect GPS satellite malfunctions.

4.5 Combat Operations and Electronic Countermeasures

GPS receivers are susceptible to disruption by enemy jamming in critical target areas by careful placement of an array of jammers, each having a power of only 1 W.

There are two approaches to avoiding the inaccuracies introduced by enemy jamming. The first, for airborne weapons, is to employ GPS up to a range where jamming begins to be effective, initialize an inertial navigation device in the weapon, and have the weapon guided only by inertial navigation to the target site coordinates. Ground-based forces are less susceptible to jamming because line of sight is more difficult to achieve by enemy ground or low-altitude helicopter-borne jammers. Nevertheless, ground forces may find it advisable to raise the lower lobe of the receive antenna pattern to be even less susceptible.

The second is to increase the power from the GPS payloads a minimum of 30 decibels (dB). It will be difficult to raise the power in the GPS payload by more than 6 dB so the remainder must be from spot beams—a not too difficult modification. Increasing the power eases direct acquisition of the P code without acquiring the C/A code first, particularly since U.S. forces may be jamming it.

A next-generation dedicated military GPS system at MEO could be designed to incorporate a larger multibeam antenna in order to increase the power density on the ground. Preliminary calculations for the current constellation altitude indicate that 30-dB greater power density could be attained with an antenna diameter of 11 to 14 m, for L1 or L2. A 40-dB greater power density could be attained with a 36- to 44-m antenna. These large antennas would have another benefit in that their spot footprints would be as small as 280 to 890 miles. It should be noted, however, that the area of interference for civil users will have twice the diameter. Therefore, a smaller spot and a larger antenna may be needed. On the other hand, if the civil code were placed in the nulls of the military code as described above, the interference would be strongly attenuated so that a larger antenna would not be needed.

Another way to assist the military is to use pseudolites, small local stations originally conceived to aid in civil applications such as surveying. The military code could be broadcast in the war zone from local stations, either fixed, land mobile, or airborne.

Another approach is to augment the present constellation with a combination of GEO and highly elliptic orbit (HEO) satellites or only geosynchronous satellites. The first approach could provide north polar coverage whereas the second would not. It is conceivable that the present GPS constellation would be dedicated mostly to civil applications, such as landing aircraft in dense fog with only GPS guidance. In that case, some form of military augmentation would be necessary.

A second-generation dedicated military GPS could then employ GEO constellations, similar to those of the first 621B GPS concept. This constellation could use one spacecraft in GEO and three in elliptical inclined orbits so that they appear to rotate about the GEO satellite. An alternative is two spacecraft in GEO with two other spacecraft in a figure-eight inclined geosynchronous orbit in between. Both constellations can cover about one-third of the world and be moved as an ensemble as needed.

These constellations would require antenna diameters of 28 to 110 m, and generate footprints of 110 to 330 miles. These smaller footprints would practically eliminate jamming threats in the theater where employed, and deny accurate military use to adversaries outside these areas.

The antennas could be of the inflatable design by JPL flown in the Shuttle a few years ago. Their design surface accuracy is more than adequate for this application, and they are very lightweight, though they require more space testing. Even smaller footprints with yet greater power density enhancement are possible and would be enabled by an actively controlled adaptive membrane. Ultimately, even greater gains at yet smaller weight will be possible using arrays of coherently cooperating swarms of “nanosats” to form the antenna beams. Both of these techniques are described by Ivan Bekey in a recent study[29] referenced above.

Thus solutions have been identified that can make a second-generation GPS into the system needed by the warfighters, minus conflicts with the needs of the civil community.

4.6 Payload Acquisition and Launches

The original space-based system was built, managed, and operated by the U.S. Navy. A 2-D system called Transit laid the basis for GPS. Transit operations that provided intermittent service were scheduled to end in December 1996. Transit was followed by Timation, first launched in 1964, which had improved clocks, but was still only 2-D. The last two Timation payloads were used as prototype GPS satellites.

In the meantime, the Air Force was working on a similar technique called system 621B for continuous three-dimensional (3-D) navigation suitable for rapidly moving aircraft. By 1972, a satellite ranging signal based on pseudorandom noise demonstrated aircraft positioning within hundredths of a mile. In addition, the Army was working on its own system, Sequential Correlation of Range.

In April 1973, the Deputy Secretary of Defense designated the Air Force as the lead agency and set up the Joint (Service) Program Office (JPO). The best ideas were incorporated into the new system. In December 1973, DoD approved proceeding on the first of a three-phase program, called NAVSTAR GPS.

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[29] *Advanced Space Systems Concepts and their Supporting Technologies 2000–2030*, Aerospace Report, 7 July 1998.

The first two GPS payloads were refurbished Timation satellites launched in 1974 and 1977. They operated for only short periods, but proved the principle that time derived from satellite-based atomic clocks and precision ranging from spread spectrum radio signals could be used to passively derive accurate position and time.

Between 1978 and 1985, the Air Force launched eleven Block I satellites built by Rockwell International, Space Systems Division (now part of Boeing). One was lost to launch failure. Others failed by deterioration of their clocks or altitude control, but many continued to operate more than 10 years, well beyond their design life of 3 years.

The first Block II payloads, also built by Rockwell, were launched in February 1989. The launch of the 24th Block II payload in March 1994 completed the GPS constellation. IOC was formally declared in a joint announcement by DoD and the Department of Transportation (DoT) in December 1993. Full operational capability was declared by AFSPC in July 1995.

Replacement satellites, Block IIR, have been built by General Electric Astro Space Division (now Lockheed Martin). Twenty-one satellites were built and the assembly line is now closed. Thirty-three follow-on Block IIF satellites are planned for procurement by the Air Force.

The AFSPC IRT was commissioned to address GPS Block III, but it is apparent that the IRT could influence backfits of not only Block IIF but also Block IIR.

4.7 Management

The original navigation system was managed and developed by the Navy as described above. The program is now in the Air Force budget and managed by a JPO at SMC. Funds for GPS, which compete with other Air Force programs and DoT requirements, are met by Air Force expenditures—a less than satisfactory procedure.

The AFSPC IRT is proposing a more equitable management and funding structure that will not be described here because it is in discussion at various levels of the U.S. Government.

4.8 Improvements in Timing—Application to Spacecraft and Payloads

Accurate location of U.S. space payloads employing GPS is permitting more accurate location of activities being measured by these payloads. Future application would permit more accurate location of targets. In certain instances the GPS payload antenna cluster will need to be changed for space applications because the antenna patterns now point downward.

Incremental improvements in timing are possible, as described above, simply by eliminating sources of error, such as overseas ground relay and control stations, that were included in the initial system deployment. Timing accuracies 10 to 100 ps will permit, for example, placing a cluster of reflectors in space accurately pointed and positioned in phase.

Timing accuracy of 10 ps corresponds to approximately 0.3-cm position accuracy. From there, a local cluster positioning system, perhaps employing lasers, would accomplish its job more easily.

4.9 Research and Development for GPS: Countermeasures and Counter-Countermeasures

GPS was designed with an extremely low average power level. In order to have a reasonably detectable signal spread spectrum, the military GPS receiver first acquires the C/A code, then locks on to the P code. The C/A code for civil users lies in the middle of the P code band as described above.

The arrangement presents several intertwined combat issues that are outlined in the for official use only appendix.

4.10 Recommendations

- Separate as much as possible the band occupancies of the civil C/A codes and the military P codes.
- Improve military operations capability against enemy countermeasures by raising the power density in the battle area.
- Arrange for direct acquisitions of the P code.
- Turn off SA in exchange for whatever hardships are thrust upon the civil users by the first two recommendations.
- Improve timing accuracy by incremental removal of inaccurate elements.
- Plan techniques, components, and systems that can take advantage of this improved accuracy.
- Follow the management recommendations made by the GPS IRT.
- Conduct the R&D activities recommended above.

5.0 Space-Based Electro-Optical (EO) (Visible/Infrared) Systems

5.1 Introduction

See the for official use only appendix for discussion of EO background.

5.2 Space-Based EO/IR Passive Sensing

5.2.1 Space-to-Ground Target Acquisition

The space-to-ground target acquisition sensor must provide a detection capability against clear and camouflaged or difficult targets. The required detection range and the conflicting requirements of excellent detection performance and area search capability dictate the inclusion of techniques such as hyperspectral and multispectral passive sensing and microscanning, which can improve detection performance with a relaxed detector angular subtense (DAS) requirement. Another method of reducing overall data requirements is to have various resolutions available. For example, in the Warfighter 1 experiment, the broadband camera has a 1-m resolution, the multispectral camera has a 4-m resolution, and the hyperspectral camera has an 8-m resolution. We can detect a target using various resolutions at the same time. We might use a broadband sensor of 1-m resolution for object shape, while sensing the spectral content at a lesser resolution.

There are two separate systems that must be discussed and sized. One is a day-only system, and the other will be a day-or-night thermal system. The day-only system will be much simpler and cheaper.

As mentioned above, a ground sample distance (GSD) of 5 m should be sufficient for the day-only system. We will assume a range of 800 km and a wavelength of 2 μm from a telescope-sizing perspective. Using the Rayleigh resolution criterion,[30] the diffraction-limited angular resolution for a circular aperture is given by Equation (1):

$$\theta = \frac{1.22\lambda}{D} \tag{1}$$

In Equation (1), λ is the wavelength, D is the diameter of the aperture, and θ is the half angle between the peak of the beam and the first null.

This corresponds to the peak-to-null half-width of the Airy disk, and is approximately equal to the full width between the half power points.[31] The full angle between nulls has a factor of 2.44 rather than 1.22, but the half power points occur at a factor of 1.08.[32] If we want the full width somewhere between the half power points and the null, we could use a factor of 1.5. Using that factor we can solve for the required telescope diameter, as shown in Equation (2):

$$D = \frac{1.5\lambda R}{GSD} \tag{2}$$

In this equation, R is the range to the target. Using Equation (2), we require a telescope diameter of 48 cm for a 2-μm design with a GSD of 5 m and a range of 800 km. We can round this to a 50-cm-aperture diameter required for the day-only sensor.

Next we consider sizing the focal plane and the scan rate. We would like to be able to search a battlefield 300-km by 300-km. If we scale the system so that it can search one-tenth of that battlefield on each pass, we will need to cover a 30-km swath on each pass. This means that for a 5-m GSD, we need to sample 6,000 pixels across. One approach to accomplish this would be to use six 1,024-by-1,024 arrays in a pushbroom mode. The 1,024 array in the direction of flight could be used for spectral information. If we use 200 bands, then we may be able to obtain some form of time delay and integration (TDI) as well (increasing dwell time by a factor of 5). We can use the extra 24 pixels in the cross-scan direction for a small overlap to register the adjacent images. A system such as the one described may require some cooling, which could be provided with a thermoelectric (TE) cooler. It would be desirable to use all passive cooling, but a TE cooler would not impose a large system impact.

A hyperspectral sensor such as the one described above will have a large output of data. If we assume a swath width of 6,000 pixels, and a satellite traveling at 7,500 m/second (s), with a factor of 5 in TDI and a 5-m GSD, we will output 1.8 million pixels per second. For 200 bands and a 12-bit dynamic range, we have 4.32 billion bits per second. In reality we don't need 200 bands for any single target background combination. If we assume we can output only 20 bands, we drop this requirement by a factor of 10. If, however, we go to a 16-bit dynamic range we will obviously increase the required data rate. We suspect we will not have to output more than 12 bits of dynamic range, although it may be useful to collect data at the 16-bit level, then compress the data in some fashion prior to transmission.

A day-only system with a 50-cm telescope could also provide higher broadband resolution in the 0.4- to 0.9-μm region. Using Equation (1) but substituting a factor of 1.5, we calculate a GSD of about 2 m at 0.9 μm and 1 m at 0.4 μm. To provide such a data set, more or larger focal plane arrays (FPAs) would be required, although the data rate would be lower since we would be using only a single band.

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[30] Joseph W. Goodman, *Introduction to Fourier Optics* (San Francisco: McGraw-Hill, 1968), p. 65.
[31] Merrill I. Skolnik, *Introduction to Radar Systems* (New York: McGraw-Hill, 1962).
[32] Ibid.

A GSD of 1.5 to 3 m will be required to detect targets in clutter using a set of three optimum thermal bands.[33] It may be possible to relax this GSD requirement somewhat when using hyperspectral thermal imagery (greater than 100 bands), but we do not expect a significant relaxation. For targets in the open, lower resolution may be used. Also, as mentioned above, we may be able to use a sensor with multiple resolutions, depending on the spectral band content, such as employed in Warfighter 1. For an orbit of 400-km altitude we need a noise-equivalent spectral radiance (NESR) of 0.25 μflicks with two bands of less than 200 nm in width, and an NESR of less than 0.75 μflicks for three or more bands.[34] These NESR results are based on a signal-to-clutter ratio (SCR) of 8 being required for adequate target detection. A large number of bands as represented with a hyperspectral imager were not analyzed, although the data were collected to allow analysis. The same reference shows that if high probability is required, an NESR of 0.1 to 0.3 μflicks is needed because of variation from one target-clutter combination to another.[35] If more bands are used, then the allowed NESR level will increase. With 10 bands, an NESR of up to about 1 μflick is allowed. High performance will be achieved with nadir viewing angles much more easily than at lower viewing angles because of the need to remove atmospheric effects. That is much more difficult at off-angle viewing since there is more atmosphere to remove.

Consider the cases of 1.5- to 3-m GSD at an 800-km detection range and a 700-km sensor platform orbit. This allows detection at up to 387 km either side of nadir and corresponds to angular resolutions of 1.9 and 3.8 microradians (μrad). Using Equation (2), a GSD of 3 m, a 9-μm wavelength, and a range of 800 km means a telescope of 3.6 m diameter. For a GSD of 1.5 m, the same assumptions result in a telescope diameter of 7.2 m. For affordable launch vehicles and telescope weights, these diameters highlight the need for deployable optics of reasonable cost. If we can obtain good clutter discrimination in the mid-wavelength IR (MWIR) region, then smaller apertures will provide the necessary ground range resolution, but data have not shown good SCR at night in the MWIR region of the spectrum.[36] Lower orbital altitudes will allow improved resolution with smaller apertures, but orbit lifetime will decrease unless there is a method of boosting the orbit to eliminate orbital decay. Table G-5 summarizes the various required telescope diameters.

Table G-5. *Required Aperture Diameter for Thermal Hyperspectral Systems*

Range (km)	***GSD (m)***	***Wavelength (μm)***	***Diameter (m)***
800	3	9	3.6
800	1.5	9	7.2
500	3	9	2.25
500	1.5	9	4.5
800	3	3.5	1.4
800	1.5	3.5	2.8
500	3	3.5	0.875
500	1.5	3.5	1.75

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[33] Eismann and Radcliff.

[34] Craig R. Schwartz and John N. Cederquist, *Brassboard Airborne Multispectural Specification Program, Phase 3: Image Measurements and Analysis,* Vol. 2, *Spectral Sensor Detection Performance Study,* April 1996, WL-TR-96-1070, pp. 78–79.

[35] Ibid.

[36] Eismann and Radcliff.

If we assume a 2.25-m telescope based on a hyperspectral sensor using about a 9-μm wavelength and a range of 500 km, then we can also use a 3.0- to 4.1-μm wavelength broadband imager for spatial resolution. The broadband sensor would have about a 1-m GSD. This combination should be very effective for target detection. In addition, microscanning can be used to provide higher effective resolution with a larger DAS. Random microscanning combined with electronic stabilization is a very attractive method of increasing spatial sampling while making stabilization more affordable. This can reduce the GSD to about 1.5 m for long-wavelength infrared (LWIR) hyperspectral imaging, and about 0.5 m for broadband MWIR imaging. Each detector will, however, view areas twice the GSD at any instant.

Covering the desired FOV will be more difficult for the day-night thermal hyperspectral IR. If we assume a DAS based on subtending 3 m, then covering a 30-km swath will require 10,000 detectors. This is a very large number of detectors. It means ten 1,024-by-768 detector arrays. If we decide to reduce the requirement to a 20-km swath, then we have 6,667 detectors across in a pushbroom mode. We will assume seven 1,024-by-768 LWIR arrays, providing a swath width of 21 km, with the same small overlap between arrays we assumed for the day-only sensor.

Step-stare or windshield-wipe scan approaches (explained below) may also be used to cover the search area.

Sensors in orbit have high velocity, providing a large search area versus time, even for cases in which a narrow area is searched. Assume an orbital velocity of 7,500 m/s, and the area searched is 150 km^2/s for the 20-km swath and 225 km^2/s for the 30-km swath. The longer-range capabilities below allow search of areas to either side of the satellite orbital path on the earth rather than just at nadir.

For classic Johnson detection criteria, a 3-m GSD would mean we could detect only targets with a minimum dimension larger than about 6 m.[37] For a cluttered situation detection, false alarm probabilities would not be acceptable even for these large targets because the Johnson criteria do not apply in heavy clutter. In heavy clutter, even larger targets would be required for detection.

Hyperspectral or multispectral sensing has a good chance of obtaining necessary detection and false alarm probabilities with samples this large even against heavy clutter. Microscanning allows the preservation of spatial detail even with a larger DAS for supporting spectral and combined spatial-spectral detection methods. In addition, as mentioned earlier, we can have a broadband sensor with higher spatial resolution, and then combine the results. Adding polarization as a discriminant may increase the allowed GSD, thus allowing use of a telescope with a smaller aperture diameter.

Considering an optimal multispectral three-band design (8.7-, 9.15-, and 9.35-micron band centers; 200-nm bandwidth), the FPA choice is essentially limited to mercury cadmium telluride (MCT) in the near term with the potential for multiple quantum well gallium arsenide (GaAs) in the future (unless one is willing to provide a 20° cooler, necessary for extrinsic silicon focal planes). Typical 640- by 480-element MCT arrays with 20-micron pitch are being developed. For a space system, in the relatively near term, we can consider a device of 1,024 by 768 elements. For current charge capacity/multiplexer well sizes, even with the limited spectral bandwidth, the FPA must be operated at a high frame rate (low dwell time) to avoid saturation in the thermal IR. This is desirable anyway because of the interest in electronic stabilization and random microscanning.

Significant cost savings may result if fine stabilization can be performed electronically. With the array reading out at 500 hertz, fairly modest pointing means will provide adequate stabilization within the frame time. Therefore, if frame-to-frame registration can be accomplished digitally, it will obviate any

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[37] J. Johnson, “Analysis of Image Forming Systems,” Proceedings of the Image Intensifier Symposium, AD 220160, U.S. Army Research and Development Laboratory, Ft. Belvoir, VA, 1958, pp. 249–273.

mechanical fine stabilization and allow the needed coadding for sensitivity improvement. There are two added benefits. First, there are gaps in the FOV for some on-chip filtering approaches, which can easily be filled in through this process with the aircraft forward motion and digital registration. Second, the jitter will cause subpixel shifts between the coadded frames, which, after proper estimation and correction, can result in an effective microscan resolution improvement.

A step-stare approach may be employed in which all of the pixels are used all of the time. This hyperspectral approach has been demonstrated and is an interesting alternative if hyperspectral rather than multispectral sampling is employed. Jon Mooney invented this approach, called a Chromotomographic Spectral Imager, for AFRL.[38]

The above discussion of a thermal IR hyperspectral system concludes that such a system should be developed. Furthermore, the use of deployable optics would make the development affordable. Exact swath widths to be utilized, GSD, orbit altitude, number of FPAs, multiplexer characteristics, and other sensor design specifics need to be studied.

5.2.2 Space-Based Air Target Acquisition and Identification

Air target acquisition is an issue of detecting a small target against a cluttered background. A nominal DAS on the order of 100 μrad is likely to be used for a high-performance air-to-air IR search and track, if we assume a high-clutter environment. That is, however, for a very close range. If we assume that the DAS is for a 40-km range, and a space-based system is for an 800-km range, we would need a 5-μrad DAS to have the same ratio of target to background within a pixel. If we can use enough observables, such as temporal and spectral signatures, then a larger DAS can be considered. Staring sensors that sample at a high rate may be able to use a larger DAS because they can use higher-rate temporal sampling. For this target type, we advocate utilizing the spatial, spectral, and temporal dimensions of the moving target.

It can be seen that the DAS required here is similar to the DAS required for ground target acquisition using a hyperspectral sensor. At a range of 800 km, a DAS of 5 μrad yields a spatial resolution, or GSD, of 4 m by 4 m. For most aircraft targets this means the whole pixel is full of target, with no background in that pixel. For a cruise missile, however, the width of the missile will not fill a pixel, so some signal to noise is lost unless smaller pixels are used. Small targets such as cruise missiles are currently of strong interest. If the DAS is made small enough that at least one pixel is full of all target, then target size is not a significant consideration. Since we have defined a down-looking spectral sensing system for ground target detection with small angular DAS, we can use it for airborne targets as well. Sample rates should be high to assure we can use temporal sampling as another discriminant. Again, if we need to use a windshield-wiper scan to obtain the required coverage rate, then we will lose sensitivity because of reduced target dwell time. Larger FPAs will recover that dwell time.

5.2.3 Space-Based Aerosol/Gas Target Acquisition (Including Chemical and Biological Species)

See the for official use only appendix for discussion.

5.2.4 Missile Target and Reentry Vehicle Acquisition

IR EO sensors are the space-based sensors of choice for missile launch warning and distant cold-body (for example, reentry vehicle (RV) in midcourse phase) surveillance, acquisition, and tracking missions. At the systems level, we do not feel a need to make significant recommendations in this area since SBIRS-High and SBIRS-Low are being pursued. Also, discrimination against clutter is not a big issue for either

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[38] Jonathan Mooney, Virgil Vickers, Myoung An, and Andrzej Brodzik, "A High Throughput Hyperspectral Infrared Cameras," *Journal of the Optical Society of America,* Vol. 14, No. 11, November 1997, p. 2951.

the bright boosting missile detection or the RV against a cold background. Cold sky clutter, such as provided by the Milky Way, can, however, be an issue for detecting a cold RV.

Principal thrusts required in component technologies for this application include higher-performance FPAs, higher-computational-performance and radiation-hardened electronics, improved long-life space cryocoolers, and lower-weight structural members integrated with other required payload attributes, including a distribution network for electrical signals and power levels. These same component thrusts could be used in the systems discussed above.

For missile launch warning, component technology advances include higher operating temperature and larger-pixel-format MWIR FPAs, which reduce cryocooler cooling requirements (and associated cryocooler power consumption) and improve sensor area coverage. Given the level of electrical power consumption of current and near-term cryocoolers (and the ultimate theoretical limits imposed by the Carnot cycle efficiency), it would be attractive to raise the operating temperature of MWIR FPAs used for missile warning to a level compatible with that offered by passive cooling with space radiators (and possibly supplemented by low-power TE coolers). This goal is within reach, with 640- by 480-pixel MWIR FPAs meeting a range of operational system requirements, including sensitivity and pixel response uniformity, at operating temperatures approaching 150 Kelvin (K).

For distant cold-body surveillance, acquisition, and tracking missions, LWIR and very-long-wavelength IR (VLWIR), larger-pixel-format FPAs improve SNR for low-temperature targets and improve acquisition efficiency against all target temperatures. Detector response beyond 12 microns becomes increasingly important for this mission, since the bulk of thermal radiation for a 250-K target, for example, is emitted at wavelengths longer than 12 μm. Some RVs might be as cold as 210 K. This means a VLWIR sensor would be ideal.

High-sensitivity sensors operating against above-the-horizon scenes require LWIR and VLWIR FPAs with ultralow levels of dark current. This translates, in turn, into a requirement for ultrahigh purity of detector material (for a corresponding reduction in impurity-assisted dark current) and low-noise cryogenic detector multiplexers. The relatively high (40 K) operational temperature of the present generation of low-background LWIR mercury cadmium telluride trades favorably against the longer-wavelength and more uniform impurity band conduction silicon, due to the 10 K operating temperature requirement of the latter, which is difficult to meet with the current generation of long-life space cryocoolers.

Sensitivity improvements for space-based EO sensors that would perform surveillance, acquisition, and tracking of cold-body targets against colder background levels can be more effective with reduction of telescopic background emission and lower temperature (less than 200 K) optics than with increased aperture diameter. However, meter-class optic diameters may still be dictated for these missions by the angular resolution requirements imposed by timely and precise handover to weapons platforms of distant (~ 10^3 km) cold-body targets. Because of the long wavelength for the cold-body tracking and the small separation distances required, this is another area in which deployable optics may provide significant cost reduction, or at least the ability to use a much smaller booster.

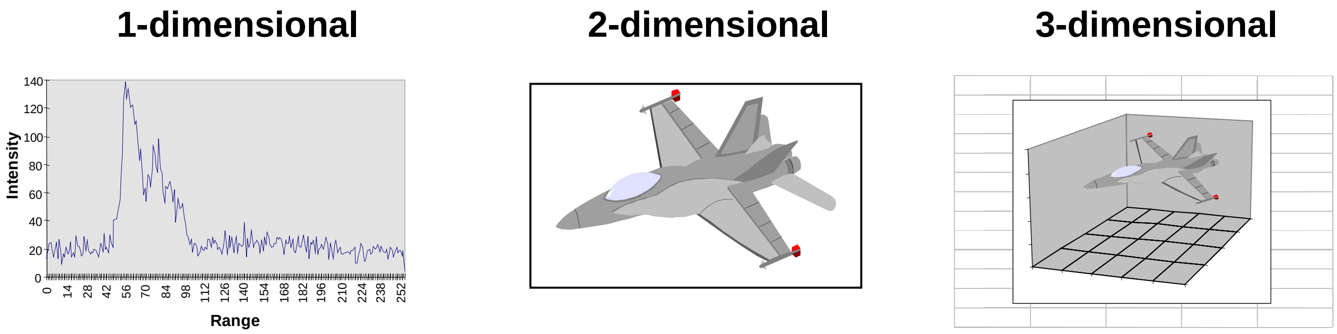
The U.S. industrial base suffers from a lack of cryogenic silicon foundries needed to fabricate detector multiplexers having the requisite levels of total dose radiation hardness for longer-term (6- to 10-year) space missions of the type described above.

5.3 Space-Based EO/IR Active Sensing

Active EO sensing can add many target dimensions and phenomenologies beyond what can be sensed with a passive sensor by itself. Because of this, EO is ideal for identification of difficult targets. The modern battlefield may consist of a mixture of friend, foe, and neutral forces. Identification of potential targets is therefore becoming a critical requirement. “Color,” high-range resolution, polarization, or vibration (for a target that has an engine running) may identify even mostly obscured targets. Traditional angle-to-angle images tend to be destroyed when a target is mostly obscured. Angle-to-angle imaging is, however, the most natural for a human observer, since it duplicates what the eye sees.

The imaging modes considered are one-dimensional (1-D), 2-D, and 3-D imaging (shown in Figure G-7). The 1-D imaging case is much like conventional real-beam radar. All of the reflected energy is gathered by a single detector, which is sampled at a high electrical bandwidth, providing image information as a function of time. Therefore, the only geometric information obtained is along the direction of pulse propagation, that is, in the range direction. Since this imaging mode is very similar to conventional radar, range-only recognition algorithms are applicable to this imaging mode.[39]

The second picture in Figure G-7 is a 2-D image, like a standard television image. The last image is a 3-D image. Because of the wavelength, the angle-to-angle imaging has better resolution than passive IR imaging. High bandwidth will also allow high-range resolution. For ground targets, the Air Force is developing 2-D imaging sensors under the Enhanced Recognition and Sensing Ladar (ERASER) effort.[40] There are also technology developments for 3-D imaging, especially in the FPA area. AFRL has an effort to develop a 32-by-32 array capable of reading range on each pixel, as well as angle-to-angle information.[41]


1-dimensional

2-dimensional

3-dimensional

Figure G-7. *1-D, 2-D, and 3-D Imaging*

Figure G-7 shows imaging in the three spatial dimensions. Many other dimensions are available, including wavelength and velocity/vibration. Polarization is of course another discriminant that can be used, and even such things as fluorescence can be exploited. With high-bandwidth ladar, a rich dimensional space is available for sampling the target. Figure G-8 shows a plot of various material reflectivities versus wavelength. This is the same for passive and active spectral sampling approaches, but the active spectral sampling allows very narrowband sampling with high SNR. When combined with beam steering approaches, this narrow spectral sampling can be provided over a wide angle. This is difficult for passive spectral-based sensors. Active spectral sampling is ideal for gas species, a currently popular requirement.

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[39] Larry Barnes, TeMatt Dierking, Fred Heitkampt, and Clare Mikula, “One-Dimensional Direct Detection LADAR Signature and Automatic Target Recognition for ERASER (Enhanced Recognition and Sensing Ladar) Utility Analysis,” Active IRIS, 1998.

[40] Frank Kile and Larry Barnes, “Enhanced Recognition and Sensing Ladar (ERASER) Long Range Laser 2-D Imaging,” Active IRIS, 1998.

[41] Richard D. Richmond, Roger Stettner, and Howard Bailey, “Laser Radar Focal Plane Array for Three-Dimensional Imaging (Test Results),” AeroSense Symposium, Conference 380, Orlando, FL, 13–17 April 1998; and Richard D. Richmond, Roger Stettner, and Howard Bailey, “Laser Radar Focal Plane Array for Three-Dimensional Imaging,” Laser Radar Technology and Applications, *Proceedings of SPIE*, Vol. 2748, June 1996, pp. 61–67.

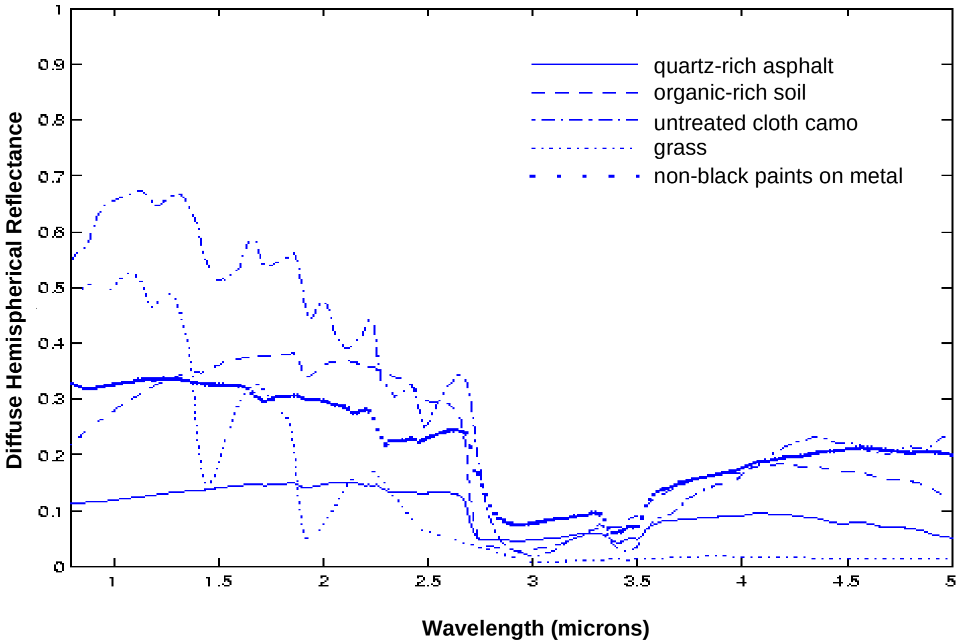

Figure G-8. *Spectral Reflectivity vs. Wavelength*

The velocity dimension can be explored using the Doppler effect. Equation (3) gives the frequency shift created by Doppler shift:

$$\nu = \frac{2V}{\lambda} \qquad (3)$$

In Equation (3), ν is the frequency, λ is the wavelength, and V is the velocity. This means the high frequency of optical systems creates a high-frequency Doppler shift and makes coherent optical systems very sensitive. Optical Doppler shifts can measure such low velocity that micron-level amplitudes of vibrations create high enough velocity to be measured. We can also measure very small object velocities.

Next we will look at potential sizes of ladar systems. Table G-6 provides rough estimates of range against hard targets for various cases. A single-pixel sensor system is very reasonable in power and aperture requirements. Such a system, however, will need a high repetition rate if an angle-to-angle image is to be formed. Average power is the same whether a snapshot imaging system or a scanning system is used. In Table G-6, we have included attenuation for penetrating weather, including thin clouds.

Table G-6. *Multiple-Pixel Illumination Range, Energy, and Aperture Requirements*

Pixels Illuminated (#)	*Energy per Measurement (Joules)*	*Frame Time (s)*	*Prime Power Requirement (W) (7% eff)*	*Cross Section (m^2)*	*Aperture Diameter (m)*	*Attenuation (dB)*	*Range (km)*
25 x 25	2	0.1	285	0.096	2	0	1,064
5 x 5	2	0.25	2,858	0.21	2	10	1,574
5 x 5	2	0.25	2,858	0.03	2	20	575
25 x 25	5	0.25	285	0.027	2	10	572
25 x 25	4	0.25	285	0.058	0.75	6	305
10 x 10	4	1.5	285	0.26	0.75	6	651
10 x 10	5	1.5	285	0.31	0.5	6	476
5 x 5	5	12.5	285	1.23	0.5	6	950
5 x 5	2	2.5	285	0.52	0.5	6	618
5 x 5	2	2.5	285	0.54	0.75	6	932
5 x 5	0.8	1.0	285	0.217	0.75	6	590
5 x 5	1.2	1.5	285	0.31	0.75	6	705

For snapshot imaging, more energy is required per measurement but not per image. The difference is that a measurement in a snapshot image is a complete image. In a scanned image, each measurement is a single pixel, and then the image is formed by multiple measurements. If we assume flood illumination of an area 25 by 25 pixels, the energy requirements will increase by a factor of 625. Table G-6 also assumes a target reflectivity of 10 percent. For area targets we can assume a certain reflectivity, and calculate the cross section by multiplying reflectivity by pixel area. Deployable optics to enlarge the available aperture would also be very useful. An aperture of a few meters deployed to provide the required GSD for a spectral-based ground detection sensor would lower required laser power and required power from a solar cell array. It would also provide more imaging for cloud penetration.

If advanced technology is assumed, we might consider deployable optics 2 m in diameter launched on a Miniature Sensor Technology Integration bus. In this case, assume we have a 0.7-m-diameter hexagon, with six other 0.7-m-diameter hexagons stowed in a stacked arrangement. When deployed, these seven hexagons would fit together to form a 2.1-m-diameter hexagon. If advanced capabilities are considered, then much more power might also be available from a deployable solar cell array. That is the reason for the entries that would use almost 3,000 W of prime power.

Another very useful mission for ladar in space is that of measuring winds. Operational commands consistently rank wind measurement high on their wish list. If we provide a Doppler-capable ladar on orbit so that we can measure the velocity/vibration dimensions of a hard target, then we will automatically have a wind velocity measurement capability from space. We feel this will be a very useful military capability for denied areas.

Hard targets have a substantial cross section, which makes power requirements low compared to aerosol targets. Of course, for the gas cloud identification problem we can bounce the laser beam off the ground and look at the two-way path absorption through the gas cloud. This provides much higher return than using backscatter directly off the cloud. Ladar is ideal for gaseous chemical identification because we can use very narrow spectral bands. It has sufficient power in the band, however, and we can use wide-angle beam steering. We also do not need an array of samples, such as discussed above for hard target imaging. A single beam or sample through the cloud will be sufficient. If aerosol backscatter is used to identify the chemical, then power requirements are essentially the same as wind sensing. If, however, backscatter off the ground is used, with spectral amplitudes to identify chemicals based upon absorption en route to and from the ground, then hard-target cross sections can be used, and lower power requirements are applicable.

For chemical sensing, either LWIR or MWIR lasers can be considered. Most work to date has been in the LWIR. This includes the Non-Proliferation Airborne Light Detection and Ranging (LIDAR) Experiment program run jointly by AFRL and the Department of Energy (DoE).[42] There is a large Phase III Small Business Innovative Research effort being run by AFRL to develop an MWIR sensor for environmental sensing.[43]

5.4 Recommendations

- Exploit as many dimensions of the target as possible.
- Continue developing passive spectral-based sensors. Couple the day-night thermal hyperspectral sensor development with the development of deployable optics, and include a multifunction ladar.
- Develop other dimensions of passive EO systems.
- Develop space-based ladar systems to provide more target sensing dimensionality.
- Develop wavelength-agile laser sources in the MWIR and LWIR regions so that we can use active spectral-based sensing for gases (chem/bio) and hard targets.
- Deploy a day-only hyperspectral sensor constellation, possibly as an adjunct to the SBR.

5.5 Optical Systems, Including Deployable Optics and Relay Mirrors

This subsection discusses telescope and optical systems options, including deployable optics. We recommend development of deployable optics as a method of allowing larger space structures to fit within a given booster class. At some future time this will allow higher SNR and better spatial resolution for a given sensor constellation cost. In the near term, deployable optics may not reduce costs because of the expense associated with the additional control and processing. For weapon systems, deployable optics may be the enabler that allows a practical system to be deployed, given the size of the optics required for many weapons concepts. In addition, practical and affordable weapon-class systems will have a significant advantage for the near to medium term if large, heavy lasers that need to be refueled can be kept on the ground. This eliminates the need to boost both the laser weapon and the fuel for the laser weapon. Suitable optical systems, however, will need to be developed to enable this very desirable option.

5.5.1 High–Fill Factor Deployable Optics

If possible, we recommend filled optics, since the gain of an optical system is proportional to area. Figure G-9 shows some filled-aperture options for deployable optics.

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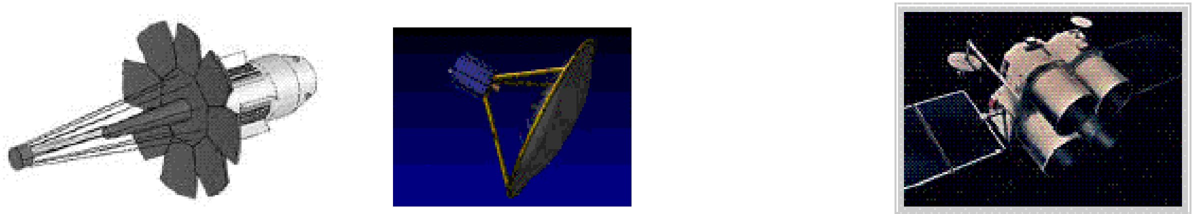
[42] John Gongolewski, Sean Jackson, Francis D’Amico, Karla Atkins, Jacob Archuleta, Donald Byrd, Bradley Cook, Charles Fite, Donald Mietz, Nicholas Olivas, David Dean, John Blackburn, David Cohn, Louis Claris, Michael Shilko, and Ronald Highland, “The Non-Proliferation Airborne LIDAR Experiment (N-Able): Introduction and System Development and Flight Test Description,” Active IRIS, 1997.

[43] Allen Geiger, “Airborne Remote Environmental Laser Mapping: Sensing the World,” IEEE, Dayton, OH, 14 May 1998.



Deployable Segmented

Inflatable Aperture

Phased Telescope Array

Figure G-9. *Filled-Aperture Options for Deployable Optics*

There are advantages to each of the concepts shown. The flower-petal-arrangement next-generation telescope is one of the nearest-term approaches for deployable optical systems. It will allow a factor-of-three increase in the effective diameter of an optical system. The phased-telescope approach is very desirable because it allows multiple smaller optical systems to be combined into a single, larger optical system. In a sense, this is not a deployable system in that nothing necessarily folds out, but it does allow us to build an optical system on orbit, so many small vehicle launches can add up to the same as one much larger vehicle launch, including the possibility of assembling optical systems much larger than any system that can be launched with current boosters. The inflatable-aperture concept shown in Figure G-9 is the riskiest but has the highest payoff if we can use inflatable optics, then deploy very light and very large optical apertures. Correcting for such a system will require both the best possible mechanical curvature and significant optical correction. Potentially, we can use a liquid crystal corrector plate to adjust for the imperfect figure of the mirror. If the figure of the mirror does not change very rapidly, then thick liquid crystal compensating optical systems can be used. This will allow many wavelengths of correction to occur. A current liquid crystal system can achieve about 1 μm of optical path difference (OPD) in about 1 millisecond. Time response of a liquid crystal optical path delay element scales with the square of the layer thickness.[44] Table G-7 gives liquid crystal corrector estimated time response versus OPD provided. Table G-7 assumes that nematic liquid crystals are used. If ferroelectric liquid crystals are used, then much faster responses will occur. The difficulty with ferroelectric liquid crystals is that they are in general only binary in their phase delay rather than having grayscale. Also, we should point out that to compensate both polarizations, two liquid crystal deflector plates are required. There is a good chance that motion of the inflatable optics will be slow enough to be compensated even with the nematic liquid crystals.

Table G-7. *Liquid Crystal Corrector Time Response vs. Maximum OPD Provided*

Time Response (s)	***OPD (μm)***	***Liquid Crystal Type***
0.001	1	E7
0.1	10	E7
10	100	E7
0.0001	1	Advanced
0.01	10	Advanced
1	100	Advanced

One issue that will have to be addressed in a more detailed study is the required liquid crystal correction when the beam location is changed by a large angle. There may be a significant difference in the required

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[44] Paul McManamon et al., “Optical Phased Array Technology,” *Proceedings of the IEEE,* February 1996.

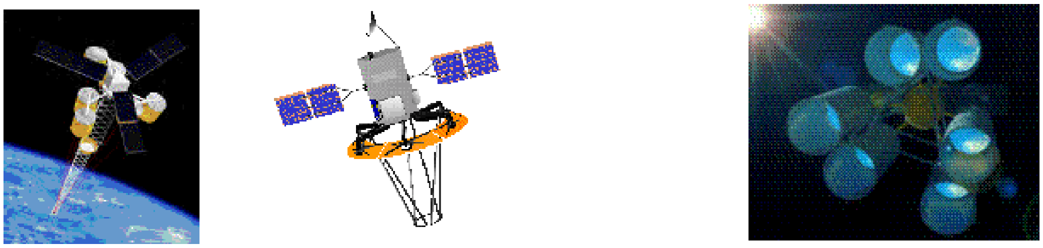
correction. If the curvature of the membrane surface requires significant correction, we may not be able to rapidly make a large change in pointing angle. This is an issue that will have to be worked.

Another approach to liquid crystal corrector plates[45] does not induce sufficient OPD for correction, but rather tilts the waveform by using grating. This method is much faster, so that speed is not a significant issue. The issue with this approach is the deflection efficiency. In addition, this is a dispersive approach, so it will be difficult for wideband passive optical sensors.

Another issue that will have to be worked for membrane optics is power handling. Since membranes are very thin surfaces, they will heat up quickly. Also, in space, no convective cooling will occur. We advise making the first membrane mirror a low-power demonstration, so that many other issues can be addressed first. Then, once a lower-power membrane mirror is functioning, move on to the higher-power applications. It is possible that high-power application telescopes with significant optical gain will be required, greatly expanding the beam so that the flux density on the membrane can be held within design limits.

5.5.2 Sparsely Filled Optical Systems

Sparsely filled optical concepts can be very useful when high resolution is required, but high optical gain is not required. As mentioned earlier, optical gain is proportional to the area of the directing aperture.



Golay-6 **Ring** **Phased Telescope Array**

Common Secondary

Figure G-10. *Sparse Aperture Concepts*

The highest resolution achievable, however, is related to the maximum spacing between the elements. For sensing concepts, high spatial resolution is often required and can be obtained by sparse array concepts as shown in Figure G-10. One of the difficulties with sparse arrays is in achieving "fill" of all the spatial frequencies. This can be done by carefully arranging the sparse element, such as occurs in the Golay-6 arrangement shown in Figure G-10. Alternatively, various spatial frequencies can be sampled at different wavelengths to achieve spatial frequency fill. With this approach there is more latitude in arranging the various apertures.

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[45] Mark T. Gruneisen, David V. Wick, Ty Martinez, and James M. Wilkes, "Liquid Crystal Media and Devices as Real-Time Holographic Recording Media for Large Aberration Compensation," Paper 3475-08, SPIE 43rd Annual Meeting, 19–24 July 1998.

5.5.3 Recommendations

- Develop deployable optics capability for space systems. For a first demonstration, consider a day-or-night thermal hyperspectral imager in conjunction with a space-based ladar. This will allow the first development to avoid the requirement for handling high power.

5.6 Space-Based Laser Weapons

During the Gulf War our Patriot missile defense systems were able to hit the Scud missiles being used by the Iraqis. Even after the defense systems hit the incoming missiles, however, the debris continued; hence significant damage occurred. As a result of that experience, we are developing an airborne laser (ABL) weapon system with the objective of killing theater missiles during the boost phase. If we can accomplish this, then the debris will fall back on the attacking nation. This development is significant for theater missiles with conventional warheads, such as we saw during the Gulf War. It is even more important for more-lethal chemical, biological, or nuclear warheads. For this class of warheads, boost-phase intercept is critical.

The ABL can be developed to be very effective as a boost-phase intercept weapon with a limited range. It is designed for addressing the theater missile threat. For longer-range missiles, beyond the kill radius of the ABL, or if an ABL is not already deployed to a theater, it would be highly useful to have an SBL available as a boost-phase intercept option. Chemical laser weapons have been under development for a long time and will not be discussed here, but of particular interest are the hydrogen fluoride (HF)/deuterium fluoride laser under development for the SBL, and the oxygen iodine laser under development for the ABL. If a ground-based laser (GBL) is used in conjunction with relay mirrors, then one of the above lasers would probably be used. The only difference would be the need for a somewhat more powerful laser to account for losses in the atmosphere and at each mirror. At this time, we find no compelling argument in favor of an SBL over a GBL and orbiting beam directors. One option that has not been thoroughly explored is a combination of ground- and space-based lasers. It may be useful to investigate this option.

This section will explore two advanced concepts. One is the relay mirror concept utilizing a GBL. The other is an electric-powered concept that eliminates having to boost fuel at the expense of requiring on-orbit power.

5.6.1 Relay Mirror–Based Laser Weapon Concepts

Alternatives to a chemical laser include the relay mirror, in which the laser stays on the ground and only the beam goes into space, and a longer-term approach in which rechargeable electric power, possibly solar thermal, is used to power a solid-state laser such as a diode array. Relay mirrors could redirect the beam to any location on the earth using multiple bounces. This approach avoids the requirement for refueling, but is in some ways more complex because of the number of mirrors.

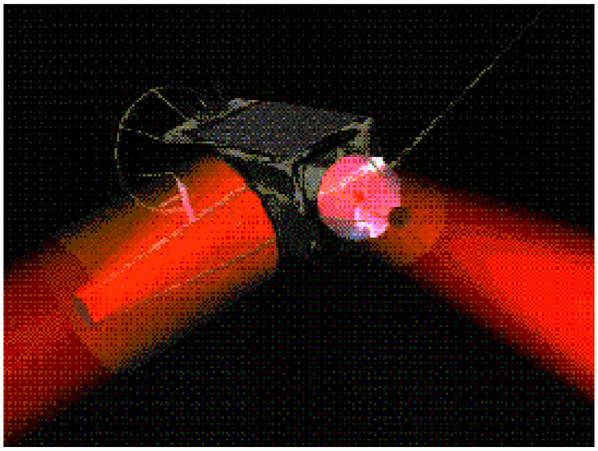

Figure G-11. *Relay Mirror Concept*

We recommend investigating a relay mirror concept in conjunction with developing affordable deployable optics. The required accuracy to deploy a relay mirror system was demonstrated years ago.[46] Figure G-11 shows a fighting mirror concept in which the beam is accepted from one direction and redirected in another. This approach will require excellent adaptive optics technology to get the beam from the ground up to space and hit the first mirror with high efficiency. The Starfire Optical Range (SOR) at Kirtland AFB, New Mexico, demonstrated just such adaptive optics capability. Recently SOR was able to achieve higher resolution from the ground than has been achieved by the space telescope.[47] This shows that it is possible even for noncooperative targets to remove the atmospheric effects to the necessary degree so that the beam can be transmitted with high efficiency to space. In laser propagation from the ground to a relay mirror, the relay mirror satellite would be designed to have a cooperative beacon positioned correctly in the point-ahead direction (probably on an extendable boom, as was done on the LACE satellite). This beacon then provides a “perfect” reference for both tracking and atmospheric compensation using adaptive optics. With a beacon in the optimum location and plenty of signal, you can expect to get substantially better beam control performance (necessary for engaging uncooperative targets) than possible with the laser guidestar technology under development at SOR.

The necessary laser on the ground will of course require higher power than if the laser were in space, because there will be losses at each mirror. However, since the laser is on the ground, it can be significantly larger and still cost less than a laser placed in space.

For access to targets around the world with a relay mirror system, it is necessary to invoke relay-to-relay links. To minimize the link losses with this architecture, it will probably be necessary to develop off-axis deployable telescopes in order to eliminate the losses associated with the secondary mirror obscuration inherent in on-axis telescope design. An on-axis design might be acceptable for some low-power applications, but the overall link efficiency would probably be unacceptably low for applications requiring higher laser power.

While it is not an exact comparison, we could look at the relative costs of the space telescope versus the SOR as some indication of the differences in cost. There is a factor of about 25 in relative costs for those two telescope systems. There will also have to be a number of sites at diverse locations in order to have a high probability that clouds will not prevent the laser beam from reaching space. It has been shown that with three sites selected carefully we have a greater than 99 percent probability of clear line of sight to

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[46] P. Kervin, J. Anspatch, J. Sullivan, et al., *Relay Mirror Experiment/Wideband Angular Vibration Experiment Report,* PL-TR-91-1088, Secret Report, January 1992.

[47] Private communication during SAB 1998 Summer Study Payloads Panel Meeting at Kirtland AFB, NM, April 1998.

space from at least one site.[48] Once the beam is in space it can be redirected to any location on earth, although we do have to figure on a loss budget for each redirection.

Another interesting use of relay mirrors is in conjunction with the ABL. If a target is too far away for the ABL to kill directly, the ABL might be able to direct its beam to a relay mirror, which would redirect the beam to the target. In spite of the loss at each mirror, there is a possibility that the final target irradiance would be higher than provided at long range directly by the ABL because the relay mirror optics would be larger than the ABL optics, thus providing a narrower beam and higher "antenna gain." Also, it might not travel through as long an atmospheric path.

Another option to be considered is a combination of relay mirrors, GBLs, and SBLs. In such an architecture, the SBL might handle rapid-response threats while GBLs handle threats that allow a slower response.

5.6.2 Electric-Powered, Solid-State, Space-Based Laser Weapon Concept

This section will postulate an advanced technology, an electrically powered weapon concept, to achieve an affordable constellation of laser weapons in space. The potential advantages include the following:

1. Elimination of the need to refuel the weapon, as in the case for spaced-based chemical lasers.
2. Minimization of the risk of hazardous chemical spills in space or during launch.
3. Increased storage lifetime (on satellites).
4. Enabling use of solar power to recharge laser weapons.
5. Modules that can be used for many other functions, such as LIDAR, or imaging and surveillance, when not used as weapons. Since the systems are rechargeable, there is essentially no cost to use them for other functions such as sensing.

The purpose of this section is not to conduct a thorough feasibility analysis, but to consider rough sizing of such a potential advanced system and to determine what development would need to occur to make such a system feasible. One part of this concept is the idea of using a multiple number of weapon modules aimed incoherently at the same spot to achieve a kill. This is naturally based on the assumption that the amount of power required to kill might be more affordably achieved with reasonable size for the power system, telescope, and laser. Thus, even if an individual weapon module is not large enough by itself, a reasonably sized ensemble can be powerful enough to kill. It is also interesting that a single module could not be called a laser weapon. Only in the aggregate can the ensemble be called a weapon.

For sizing purposes we will assume 100-kilowatt (kW) laser modules and a telescope with an aperture 4 m in diameter. To adequately evaluate this concept, we would need to revisit these gross module size assumptions on the basis of reasonable device sizing break points. Such a concept would require inexpensive large-aperture telescopes. A system concept such as the one described above would require a large number of satellites, so we would need to set up a contiguous production line, and costs would need to decrease over the course of a fabrication learning curve.

The electric-powered laser concept is obviously less mature than chemical lasers that have been in development for many years and have demonstrated weapon-level power outputs. Nevertheless, if current low-power devices can be scaled to the necessary levels, the many benefits of electric-powered lasers would make them very attractive as the long-term solution to directed-energy weapons in space.

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[48] Barry Hogge, briefing to the SAB 1998 Summer Study Payloads Panel Meeting at Kirtland AFB, NM, April 1998.

5.6.2.1 Constellation Size for a Weapon Effect

In Table G-8, we estimate the number of the modules required to achieve a kill, assuming 100-kW laser modules are used. We will assume a factor of 1.5 λ/D for the spot diameter. Table G-8 gives the spot size, flux, and number of satellites versus range. We have neglected atmospheric attenuation, which will result in a need for more satellites. We will assume that 34 megajoules/m^2 are required for a kill (2 megawatt/m^2 for 17 seconds).[49] Obviously there are a number of different assumptions that could be used here, but once again, this is just a rough sizing estimate. It can be seen from Table G-8 how critical deployable optics are to such a concept. The most significant point here is that a very reasonable-size constellation can be used to achieve the desired flux density.

Table G-8. *Number of 100-kW Weapons Modules Required vs. Range*

Telescope Diameter (m)	*Range (km)*	*Spot Size (cm)*	*Flux Density (kW/m^2)*	*Laser Modules Required (#)*
3	1,000	53.0	453	5
3	1,250	66.0	290	7
3	1,500	79.5	201	10
4	1,500	60.0	358	6
5	1,500	48.0	560	4
6	1,500	40.0	805	3

5.6.2.2 Lasers

The main issue here is whether 100 kW of diffraction-limited laser beam can be obtained and if so at what cost and weight. For this report, we shall cite examples of diode-pumped solid-state lasers only. Thorough evaluation is recommended for future studies. In the future, direct diode lasers could be used, but they are judged to be less mature because of the requirement for phasing.

Recent advances in diode-pumped neodymium (Nd):YAG and ytterbium (Yb):YAG lasers have led to remarkable results. Lawrence Livermore National Laboratory (LLNL) recently achieved an Nd:YAG laser emitting at 1.06 μm with 600-W CW output and 20 percent overall electrical-to-optical conversion efficiency.[50] As high as 950-W CW output power was attained from a Yb:YAG laser at 1.03 μm by a group at Hughes Research Laboratories.[51] Although these numbers are substantially lower than the goal of 100 kW, we argue that power scaling may be feasible because (1) there have been studies indicating that solid-state lasers can be scaled up using multiple stages of solid-state laser amplifiers, and (2) substantial expertise can be leveraged from a number of previously funded programs at LLNL and elsewhere by DoD and DoE on very high-power lasers.

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[49] "The Resurrection of Star Wars: Ballistic Missile Defense (BMD)/Laser Weapons," *IEEE Spectrum*, September 1997.

[50] Dr. Hao-Lin Chen, Deputy Director of AVLIS program at LLNL, private communication, 24 June 1998.

[51] D. Sumida, H. Brusselbach, R. Reeder, and R. Byren, "Kilowatt Yb:YAG Laser Illuminator," Active IRIS, Tucson AZ, March 1997.

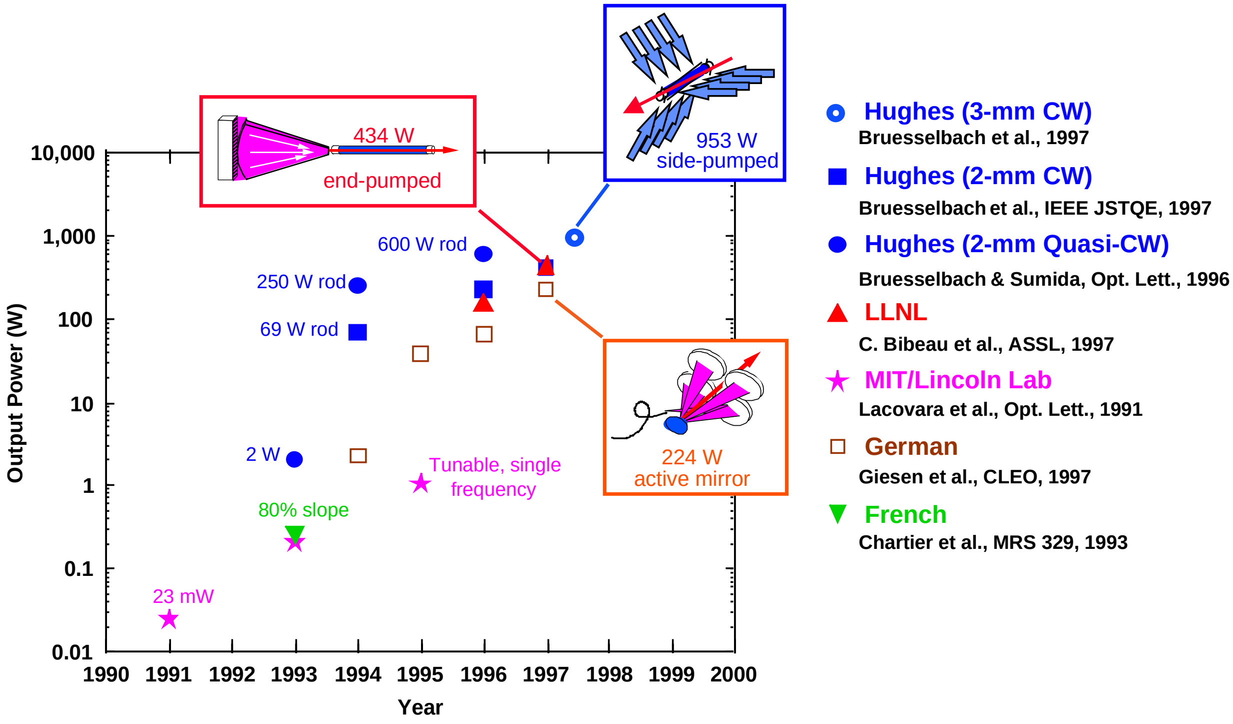

Figure G-12. *Current Diode-Pumped Laser Development*

In order to achieve high overall efficiencies of greater than 20 percent, the solid-state lasers should be pumped by diode lasers. In the LLNL case cited above, the laser pumping efficiency from diode laser to Nd:YAG output is as high as 60 percent. Using this number, approximately 150 kW of diode laser power is required for 100 kW of solid-state laser output. Typical high-power diode lasers are edge-emitting laser bars, which are expensive at $25 per watt. For 150-kW output, the diode lasers alone would cost $4 million. Although only incoherent diode laser output is needed (the only requirement is that the emission spectra be within a 3- to 5-nm window), it is not entirely clear how scalable diode laser power can be, given that the bars need to be assembled physically to form a stack or 2-D array and to be coupled effectively into small solid-state laser rods.

Recent advances in VCSEL present an interesting scalable and cost-effective high-power alternative. The advances include reports of 57 percent electrical-to-optical power conversion efficiency and a 2-W CW output power from an array with 66-W/cm^2 power density. Higher power density greater than 100 W/cm^2 has been achieved with lower power output. With VCSELs being wafer-scale processed and packaged, it is expected that full-wafer-size high-power arrays can be fabricated at low cost and high yield. Furthermore, VCSEL emission spectrum is naturally narrowband and more precise, providing a higher yield for pumping within the spectra window. Using a 4-inch-diameter VCSEL wafer with 90 percent yield at 100-W/cm^2 power density, one can obtain 6.75-kW output with a cost estimate of less than $5 per watt. This brings the cost of diode lasers down to $750,000 and would simplify greatly the coupling optics design, further reducing the entire module cost.

Given the rough estimate above, we believe a 100-kW laser module is potentially feasible and affordable. Detailed feasibility study and laser research are, however, highly recommended.

We have estimated a 500-kg mass for this laser, assuming the laser can heat up during operation and cool while it is recharging during the rest of the orbit. This means either the laser must be designed to operate over a wide temperature range, or substantial phase-change material must be included. As a goal, we would like the laser weight to be reduced to less than 250 kg. The number of shots will be limited by cooling and power storage. We need a single-cavity laser system with some form of beam clean-up, such as phase conjugation and spatial filters. A likely candidate will be a spinning-disk Nd glass laser in an unstable resonator design. The design could use a Master Oscillator Power Amplifier configuration. We are unlikely to do better than 15 percent electrical-to-optical efficiency with this design. One approach would be a number of 60-cm-diameter, 3-mm-thick spinning disks. The active region on the disk would be a donut with a diameter of approximately 4 cm. The disk would rotate between 200 and 300 revolutions per minute (rpm) and one would need 10 to 20 of these inside the resonator representing the master oscillator. The output of the master oscillator would be about 40 kW and would have a very good beam quality. Now, using a similar module for the amplifier, and assuming losses between oscillator and amplifier of only a few percent, with a gain per disk of $e^{(.09)}$, one could get the 100 kW of desired power with a single additional amplifier stage. A second approach, with potential for higher electrical efficiency, would be a fiber-based laser. In this case, the fiber outputs would probably need to be phased together. Some people have estimated that there is potential for up to 30 percent electrical efficiency in a fiber-based diode-pumped solid-state laser.

5.6.2.3 Electric Energy

For a 100-kW laser weapon module with a 20 percent electrical-to-optical conversion efficiency, 100 s of lasing time per orbit, and 80 percent depth of discharge, we will need 6.25 x 10^7 joules (J), or 17.4 kilowatt-hours (kWhr). This means an energy storage flywheel that weighs 115 kg, based upon 150 Whr/kg. We use the flywheel for sizing because we have data on energy storage for a given weight of a system. Other approaches should be considered, including capacitive storage. The flywheel will have to be able to dump its stored energy in a short period, and this will require careful planning so that it does not move the spacecraft and create pointing problems. In order to have 17.4 kWhr stored using solar power to charge the flywheel (assuming sunlight for one hour per orbit) we need an 18-kW solar cell array. At 200 W/kg, the solar cell array will have a mass of 90 kg. If we assume 15 percent laser efficiency, a more conservative number, then the energy that must be stored in the flywheel is 8.33 x 10^7 J rather than 6.25 x 10^7 J. This increases flywheel mass to 153 kg, and increases the mass of the solar cell array to 120 kg.

5.6.2.4 Mass

Even a 3-m telescope of conventional design would be very expensive. The NASA space telescope is only 2.4 m, but cost billions of dollars to build and launch. Primary mirrors of this size take years to fabricate, and that labor needs to be paid. Obviously we would like to use membrane optics for very light weight. There are issues of power handling as well as the figure issues discussed in the section above. If we are more conservative and assume a future mirror weight equivalent to a 1-cm-thick layer of water, the radius of the primary mirror, then we will have the masses given in Table G-9 for the primary. In Table G-9 we also assumed a telescope would weigh twice as much as the primary. These are certainly rough estimates, and may never come to pass. If, however, we can use membrane mirrors, these estimates will at some time become pessimistically high. It is also very likely that weight will scale quicker than a square law versus primary diameter, even though that proportion is assumed here. Certainly a higher scaling law is the case for the current generation of telescopes, which would be more massive than the values shown in Table G-9.

Table G-9. *Potential Primary and Telescope Weights for Moderately Optimistic Deployable Optics*

Mirror Diameter (m)	***Primary Weight (kg)***	***Telescope Weight (kg)***
3	71	142
4	125	250
5	196	392
6	283	566

If we assume a 5,000-kg laser, a 250-kg, 4-m telescope, 153 kg for the power storage, 120 kg for the solar cell array, and a 100-kg miscellaneous structure, we have a total mass of 1,123 kg per satellite. At $10,000 per pound to launch, the launch costs would be about $25 million. We expect launch costs to decrease, however. If we reduce the launch costs by a factor of three, we have a launch cost of $8 million.

5.6.2.5 Total Constellation Estimate

If we assume a 1,200-km ground range on each laser weapon (consistent with a 4-m mirror and a 1,500-km range), we can roughly calculate the number of satellites required by finding the area covered by a single system and dividing it into the surface area of the earth. We then have to multiply that number by the number of weapon modules required to simultaneously illuminate a given target. This very simplistic model yields a need for about 100 satellites for continuous coverage, or 600 satellites to have six within range at any given time (consistent with earlier assumptions on mirror size and range). Since we neglected atmospheric attenuation earlier, we might want to size the constellation for 900 satellites.

One of the interesting aspects of the above constellation is that it provides a wonderful sensor constellation. We would need almost no changes to provide a very robust worldwide ladar capability. Because of the high power available, such a sensor system could be made to see through much of the cloud layer. A number of the tasks discussed in the sensor section above would be easily performed, and would be available at almost no additional cost.

5.7 Recommendations

Pursuit of the objectives outlined above requires that DoD undertake the following R&D activities:

- Conduct a thorough feasibility study of an electrically powered laser weapon module at 100-kW optical power per module using diode-pumped solid-state lasers or diode lasers. Other power levels could be considered if there is a natural break point.
- Develop manufacturable, deployable telescope designs to attain minimum weight per given size at affordable price. This is critical to any potential laser weapon constellation.
- Understand and manage radiation effects on solid-state lasers, diode lasers, and other module components.
- Develop affordable, high-efficiency, very high-power, lightweight solid-state lasers.
- Develop affordable, high-efficiency, very high-power diode lasers, including VCSEL laser arrays.
- Develop lightweight, efficient, and affordable laser cooling schemes.

- Develop lightweight, high-efficiency solar power.
- Develop an efficient, light energy storage medium that is capable of emitting high power for a short period.

6.0 System Architecture and Integration Issues

6.1 Introduction

The doctrine of war is to follow the enemy situation in order to decide in battle.[52]

—Sun Tzu

In collaboration with the Architecture and Information Management Panel (Appendix F), the Payloads Panel examined the implications of system and system-of-systems architecture on current and future space systems.

What role should overhead space assets properly play in supporting the Air Force warfighter? Former U.S. Space Command Commander in Chief Gen Howell M. Estes III describes space-based systems as the

> Enabler of Military Operations: From Desert Storm to every exercise since, we've come to know that all military operations depend on space based capabilities. We believe space will become even more important in the future. For the needs envisioned in the next decade, our already smaller military force will be more effective because of the information available to it. *Much of this information will come from space based sensors and virtually all of it will flow through space* at some point before reaching our forces.[53]

Col Pete Worden, USAF, in an address to the Payloads Panel on 18 June 1998, described the Air Force warfighter functions as "Find, fix, track, target, engage, and assess."[54]

The time scales for performing these critical functions have shrunk, due to the relentless pace of technology. Whereas find/fix/track (surveillance and reconnaissance) might have taken days as recently as World War I, now the response time is only minutes, possibly even seconds.

Table G-10 gives the time scales described by Col Worden as being truly significant to the warfighter.

Table G-10. *U.S. Air Force Warfighter Time Scales*

Function	*Time Scale*
Combat	minutes
Air Tasking Order (tomorrow's battle plan)	24 hours
Air Tasking Order (reinforcement/replenishment)	7–14 days
Spiral Development (equipment modification or update to counter technical challenge)	18–24 months

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[52] Sun Tzu, *The Art of War*, ed. and trans. Samuel B. Griffith (Oxford: Clarendon Press, 1963), p. 140.
[53] "USAF Space Command Long Range Plan Executive Summary," Foreword by Gen. Howell M. Estes III, March 1998.
[54] Col Peter Worden, address to the SAB Payloads Panel, 18 June 1998.

Arguably, the space-based assets can place the Air Force warfighter on the "high ground" if the assets can be interoperably tasked and the output data fused into a usable result for timely support to the decision maker.

In order to prevail against threats not even currently envisioned, the Air Force requires the twin core competencies of global precision awareness and information dominance.

> **Global Precision Awareness**—The ability to reliably, accurately, and continuously collect information on the global situation; the mechanism that pinpoints targets and threats.
>
> **Information Dominance**—The ability to route the right information to the right decision maker at the right time; a mechanism to allow the decision maker to decide in battle. Dominance is achieved when Air Force decision makers possess the information necessary to effect action faster or better than any enemy.

Are space assets even considered to be assets at their current level of disposition, deployment, and interconnectivity? The most recent data appropriate to examine are the performances of space assets during the 1991 Gulf War. Maj Gen James Clapper, USAF, former Director of the Defense Intelligence Agency and Air Force Intelligence, observes that the Gulf War "served as a crucible for systems that collect, analyze, fuse, and disseminate intelligence."[55]

These carefully worded phrases fail to convey the frustrations of the Gulf War command staffs as conveyed by Gen H. Norman Schwarzkopf, Commander in Chief, Central Command. In testimony before the Senate and House Armed Services Committees, the general stated he did not regularly have the information required, and he recommended that the intelligence community develop systems "capable of delivering a real time product to [the] theater commander when he requests [it]."[56]

Synthesis of the positions presented above leads to the conclusion that in order to prevail, the Air Force warfighter must be able to follow the developing world situation in near real time, requiring

- Surveillance—to synthesize a global picture from multiple sensors
- Reconnaissance—to provide high-resolution "zoom" to areas of interest
- Global access—persistent continuous access to the entire globe
- Fusion—the timely combination of data from various sources into useful information tailored to the user request
- Data access—single-point access to required or relevant information for a multitude of users

6.2 Confluence of External Forces

A convergence of external forces (commercialization of space, budgeting uncertainties, technological evolution, mission requirements growth) mandates a structured approach to systems definition, acquisition, and operations.

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[55] James R. Clapper, Jr. "Desert War, Crucible for Intelligence Systems," in *The First Information War,* ed. Alan D. Campden (Fairfax, VA: Armed Forces Communications Electronics Association International Press, 1992), p. 81.

[56] Harry E. Soyster, "Extending Real-Time Intelligence to Theater Level," in *The First Information War*, pp. 61–62.

A variety of external factors are forming the boundary conditions for evolving the integrated air and space forces. There is no possibility to precisely foretell the future, but inexorable developments are beginning to shape the framework for future space systems. A short list must surely include the following topics.

6.2.1 Current World Situation

With the collapse of the Soviet empire in 1991, the United States no longer faces a monolithic enemy serving to focus organizational strategy. There is no expectation of facing a global peer competitor in the near future. As a consequence, the United States

> … has entered a period of strategic pause. This period offers the military an opportunity similar to the period between World War I and World War II—a time for exploring innovative war fighting concepts and capabilities. Given the continuing dynamic nature of the space environment and the long lead times necessary to develop and field space capability, there is a sense of urgency to articulate future requirements today.[57]

6.2.2 Adversary Proliferation

The single adversary no longer exists; now a wide variety of opposing forces, including state-sponsored and non–state sponsored terrorism, and fluid coalitions, act in concert against U.S. interests.

> For some, our dependence on space will offer an attractive, low cost (asymmetric) strategy for inflicting significant damage at relatively lower risk than taking on our impressive conventional forces.[58]

More ominously,

> … rapidly emerging markets for telecommunications, imagery, entertainment, personal computing, the Internet, and navigation are enabling non-state actors, terrorists—virtually anyone with a laptop and money—the opportunity to exploit directly the rich benefits from space. The broad availability of militarily useful information is eroding the U.S. historic advantage in this area.[59]

6.2.3 Hot-Spot Proliferation

A short list of the current regional conflict areas occupying a substantial portion of the available surveillance and reconnaissance assets would have to include the following:

- Serbia (in the former Republic of Yugoslavia)
- Kosovo (as a militarily distinct area of interest)
- Pakistan and India (because of the nuclear proliferation threat)
- Iraq, in particular Kurdistan (northern Iraq)
- The Middle East (Egypt, Israel, Jordan, Lebanon, and the Saudi Arabian peninsula)
- North Korea
- Selected areas of Africa (including Nigeria)

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[57] "USAF Space Command Long Range Plan Executive Summary," p. 2.
[58] Ibid., Foreword by Gen Estes.
[59] Ibid., p. 2.

These hot spots are areas in which the National Command Authority wishes to "know all" in order to act responsibly and decisively. Yet today's generation of space surveillance and reconnaissance assets were designed and deployed against the Soviet monolith, and are not optimally effective (in terms of revisit time, long-term dwell capability, multispectral capacity, and ability to "fuse" intelligence products into manageable information) for their current tasks.

6.2.4 Commercialization of Space

John Cunningham of Globalstar, a mobile satellite telecommunications company that has eight satellites in orbit and expects to put up 48 in the next year, says,

> We are on the verge of a commercial space explosion. Space related industries are growing 20 percent annually. In a few years we'll see 1,000-plus new satellites launched and about $500B spent worldwide on space applications. The inescapable conclusion is that space is becoming inextricably linked to life here on earth.[60]
>
> Over the next five years, more than 1,200 satellites are expected to be launched, versus 650 the past five years … The industry is heating up for a phenomenal period of growth … There's a revolution brewing. It's the next big wave.[61]

6.2.5 Fiscal Uncertainty

For budget outlays in future years, a level expenditure in constant dollars is the most optimistic scenario. A pessimistic scenario of declining or variable funding places stress in any long-range planning or acquisition strategy. In essence, a requirement is levied to make choices amid constrained resources while surrounded with burgeoning threats.

6.2.6 Mission Requirements Growth

The conflicting needs to deal with counterterrorism and counterproliferation efforts, humanitarian assistance, and peacekeeping operations while providing global reach, power projection, and information dominance mandate a structured long-range planning approach. For example, military operations now critically depend on space capabilities such as global communications, near–real time surveillance and reconnaissance, missile warning, weather, and navigation. Army Major Mike Birmingham, a spokesman at AFSPC, which tracks 8,500 objects in earth orbit, says that the May 1998 service outage of the Galaxy IV satellite (which disabled most of the pager service across the United States, as well as most gasoline station point-of-sale terminals)

> shows how dependent we are on space technology and how much more vulnerable we will become as more satellites are launched … It illustrates how important one satellite can be to the country … America needs to protect its vital national interests …[62]

While the reasons for the Galaxy IV failure are unknown (potential candidates include natural radiation damage and space debris impingement), it is clear that the failure was sudden and unanticipated, and that *no* contingency plans were in place. This critical dependence on space produces a related vulnerability, both military and economic, which almost by its immensity mandates a requirement to protect U.S. space systems from hostile actions, prevent unauthorized access to U.S. assets, and negate hostile space systems that place U.S. and allied interests at risk.

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[60] Ibid., Foreword by Gen Estes.

[61] Del Jones, "Dangers Lurk in Growing Reliance on Satellites," *USA Today,* 21 May 1998, p. 3B.

[62] Ibid.

6.3 Steps to Future Systems Interoperability

The positions put forth in the previous paragraphs pose the following questions:

- What are the architectural issues in crafting a space systems constellation suitable for U.S. Air Force future needs?
- Where and how can space assets be most profitably employed?

In *Air Force 2025* an operational analysis and value assessment was performed (italics added).

> The analysis team arranged each of the missions and tasks needed to reach the objective of achieving dominance in Air and Space into the general categories of awareness, reach, and power. … Each system was judged for its contribution to the *awareness* tasks of detect, understand, and direct; the *reach* tasks of deploy, maintain, and replenish; and *power* tasks to engage and survive. … There are several conclusions to be drawn from this analysis. First, according to the operations analysis done on the concepts of operations, technologies, and systems developed as a part of *2025*, the investments made in awareness versus reach and power are roughly two to three times as important as investments in the other areas. Second, there is a major increase in utility of space-oriented systems as opposed to atmospheric ones.[63]

The preponderance of research, evaluation, and assessment indicates that energy, emphasis, and development should concentrate on *awareness* (detect, understand, direct).

Regarding the U.S. overhead satellite systems, only the weather satellites and GPS (timing and navigation) are broadly accessible to the entire military user community. Unfortunately, this broad accessibility carries with it the vulnerability to sabotage and deliberate attack.

6.3.1 Barriers to Interoperability

Interoperability among elements of satellite constellations may be defined as the ability to freely interchange commands, status telemetry, tasking, and payload data among the system elements. The present suite of overhead assets is not at all interoperable.

The barriers to interoperability may be summarized as follows:

- Command and data-handling protocols (message formats, frequencies, control hierarchies) are incompatible.
- Mission (product) data frequencies, formats, and organization are incompatible.
- The CONOPS are incompatible.
    - LEO and MEO satellites require intermittent ground-transmitted tasking uploads for (present) storage and (delayed) execution. Mission data, unless transmitted through a relay, are intermittently broadcast.
    - GEO satellites (in view 24 hours per day) are customarily in continuous contact, with tasking supplied from a mix of preplanned and ad hoc sources. Mission data readouts are continuously broadcast.

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[63] *Air Force 2025,* Executive Summary (Maxwell AFB, AL: Air University Press, 1996), pp. 24–25.

- The various satellite systems were designed and deployed, and are (for the most part) operated through stovepiped organizational structures, with non-uniform:
  - Mission priority emphasis
  - Reporting structures
  - Product distribution architectures
- Data products are not "fused" (i.e., taken from multiple platforms and transformed into a timely intelligence product, tailored to the user request).
- Data products are not integrated in a common (accessible) database.
- Data products not accessible (either push or pull) to a wide range of end users.
- There is no capacity to easily and rapidly "close the loop" between
  - Tasking (information request)
  - Provision of a tactically useful result

6.3.2 Enabling Systems Interoperability

If space is the ultimate "high ground," what is the most effective means for getting there (i.e., with the least cost, the least time, and the most flexibility)? Logic dictates that maximum practical commonality is the key to overall system cost reduction, but some legacy systems will endure during the introduction of any new system or set of systems. It may well be that "attaining and maintaining superiority is as much dependent on the rapid introduction of marginal hardware improvements to existing systems and their integration with new ideas as it is on the breakthrough technology."[64]

The successful approach will likely involve a blend of enhancements to current systems, plus a revolutionary new architecture with a feature suite that includes the following:

- Proliferated satellite systems, probably commercially based
- Modular payload architectures
  - With rigorous self-testing and calibration
  - With capacity for revision or update prior to launch
  - Countering technological obsolescence
  - Augmenting changing mission requirements
  - With significant on-board processing
  - Performing on-board data thinning
  - For first-level data "fusing"
- Interoperability with existing satellite architectures (at least in a limited sense)

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[64] Ibid., p. 13.

6.4 Enabling Systems Access

6.4.1 Information System Characteristics

According to *Air Force 2025*,

> It is not information itself which is important but the architecture of and infrastructure for its collection, processing, and distribution which will be critical. … Increasingly, advantage is achieved through investments in information systems, decision-making structures, and communication architectures.[65]

In order to achieve constant global coverage that provides information dominance, the most likely architectures are sensor systems composed of ground-based (unattended ground) sensors, air platforms, and satellite platforms acquiring data in multiple regimes.

The sensor suites are numerous and proliferated, to provide a "fail soft" tolerance to outage, that is, a high tolerance for being rendered inoperable by loss of one or even multiple nodes. The sensor systems, using highly distributed commercial satellite links and networks, are constantly updating the common operating picture maintained in master databases.

The information database

> … is a pervasive network of intelligent information gathering, processing, analysis, and advisory nodes. It collects, stores, analyzes, fuses, and manages information from ground, air, and space sensors and all-source intelligence. This system has all types of sensors (i.e., acoustic, optical, radio frequency, olfactory, etc.) …[and] provides complete situational and battle space awareness tailored to each user's needs and interest.[66]

An integrated, timely product provided to any end user (strategic, operational, or tactical) who plugs in to the system, implies software intervention, possibly in the use of personal software agents (or intelligent agents). These intelligent agents would undergo a training process with the end user to assess the level of operational information required, as well as special interest areas unique to the user. Additional user database accesses allow the intelligent agent a "look over the shoulder," leading to a high degree of anticipation of user interests. The personal intelligent agent might "roam" the information databases and alert the user when information meeting user preference criteria is perceived. There are current examples of such agents, albeit in a more primitive form. For example, the Internet search tools (Lycos, AltaVista, Yahoo!, HotBot, etc.) use intelligent agents that constantly roam the Internet (server suites) to update hot links relating subject topics to databases.

6.4.2 User Authentication

System security checks to screen user access will require ingenious application of existing and emerging technologies. The system access checks will likely include fingerprint matching, retinal scans, deoxyribonucleic acid matching (possibly saliva), and voice typing (testing for duress). All of these features will likely be required, both to allow access to authorized users and to preclude and prevent attempted "forced entry" by a valid authenticated user under duress.

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[65] Ibid., p. 8.
[66] Ibid., p. 25.

6.4.3 Operator Interface

These future information system users will come from varying backgrounds, with different skill levels, training, and attitudes. Tactical users may need to access and interact with the information store while in a heightened state of stress (i.e., under fire).

A system design that meets the requirements for "users at all levels of war" may mandate the following:

- *Standardized Tasking Interface*—for example, the Microsoft Windows (3.1, 95, 98) interface in which "Print" is always a subtask of the "File" button, on *any* application.

  The information should be provided seamlessly and transparently. The future end user should have the ability to task and exercise systems without detailed knowledge of system features, and without limitations. The user is unconcerned with where or how the information was acquired. The user's request to the system *pulls* the needed information.

- *Virtual Reality Display Systems*—providing 3-D holographic displays of the situation, with voice exchanges to direct or redirect the scene presentation and tactile inputs to prompt actions.
- *Individually Deployable Intelligence Agents*—the actions of which have been fine-tuned to user expectations and requirements, *pulling* information in response to stated expectations, and *pushing* information deemed of interest. The agent might assimilate historical and current data, and provide (*push*) unsolicited cues regarding critical activities in progress.

6.5 Common Modular Architectures

Achievement of the modularity, flexibility, and functionality described in the previous paragraphs, while operating under fiscal, political, and technological constraints, mandates a "new way of doing business." Various estimates on aerospace technology developments place nonrecurring engineering (NRE) at 35 percent—40 percent of the total development budget. A clear path to achieving significant technological progress while following this evolutionary path is to undertake a rigorous program of standards development. Once employed, these system architectural standards would provide clear physical, logical, and functional interface descriptions. This standards development would surely extend to

- Interconstellation communications architectures:
  - Laser cross-link wavelengths and power densities
  - Bit rates, modulation, and multiplexing formats
  - Data bus structures
- Uplink and downlink communication architectures
- Satellite vehicle modules:
  - Packaging (physical, thermal, and radiation shielding)
  - Functional interfaces (command and data handling)
  - Data bus structures

- End-user interfaces:
    - User authentication
    - Feature suites
    - Standardized tasking interfaces
    - Operator control and display (graphical and virtual reality user interfaces)

Successful examples of system architectural standards that were or have been used to achieve a degree of interoperability include:

- *The Space-Ground Link System*—a communication standard between the AFSPC network and orbiting satellites. The standard introduced in 1966 is still in use today and describes frequencies, bit rates, modulation formats, and channelization (frequency spacing) requirements for both uplinks (ground to satellite) and downlinks (satellite to ground).
- *Transaction Control Protocol/Internet Protocol*—a standard that allows computers (servers) from diverse manufacturers to exchange data packets bidirectionally at high speeds. It forms the basic interchange mechanism for today's Internet.

This short list merely gives the basics of carefully crafted standards that have

- *Evolved* to meet a changing technological environment
- *Survived* over the long term
- *Aided* the goal of systems interoperability
- *Minimized* NRE in measurable ways
- *Assisted* innovation and ingenuity in accomplishing mission goals

6.6 Recommendations

The previous paragraphs have emphasized that investments in space provide the maximum leverage to achieving *global precision awareness* and *information dominance*, the "high ground of space" sought by the Air Force warfighter. Yet much of the available energy and resources have (in the past) chased development and acquisition of stovepiped systems that are incapable of providing seamlessly fused information with low latency.

To lower system design, acquisition, and operations cost and to provide quantum improvements in intelligence systems capability, it seems appropriate to mandate and require the application of systems architectural standards.

This leads to a recommendation that an Architectural Standards Committee (ASC) be established. The ASC's charter would encompass three tasks:

First, the ASC would establish the most appropriate system divisions in which to apply standards, as indicated in Figure G-13. The application area extends across six levels, all the way from hardware and software (level 1) to a system-of-systems (level 6).

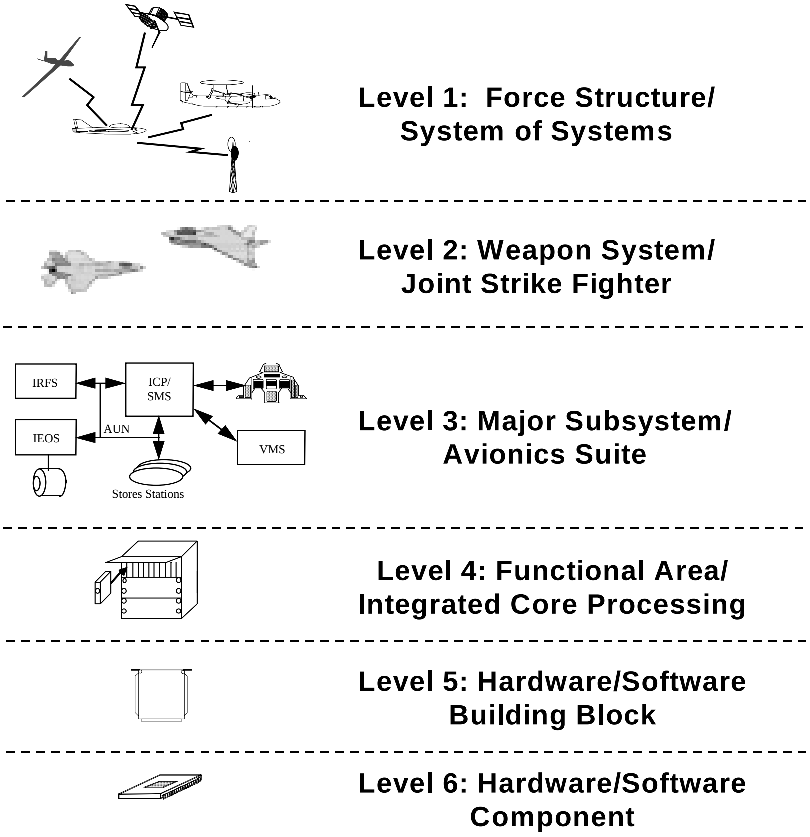

Figure G-13. *Architectural Hierarchy*[67]

Moving to an open systems architecture (accessible to participation by multiple contractors and commercial suppliers) requires the following:

- Modular partitioning
- Identification and rigorous control of interfaces:
  - Physical (power, thermal, connectors, dimensions)
  - Functional (bus protocols, instruction set, operating system)

Figure G-14 covers the definitions for an open architecture and shows a path to applying architectural standards to new development.

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[67] Dr. John M. Borky, Chief Engineer, “Open System Architecture for Avionics,” Slide 43, Presentation by Technical and Training Services, TRW Systems and Information Technology Group, 6001 Indian School Rd., NE, Albuquerque, NM 87110, September 1997.

General Attributes of Open Systems:

- **Modular Design With Mapping of Functions Onto Hardware and Software Components**
- **Mapping of Software Architecture Onto Hardware Architecture (a Block Diagram Is *Not* an Architecture)**
- **Component Interfaces That Are:**
  - **Fully Defined**
  - **Publicly Available**
  - **Maintained Through Expert Consensus**
  - **Implementable With Available Products**
- **Maximum Feasible Use of Mature, Well-Supported, Widely Used Interface Standards**

Figure G-14*.* *Some Key Terms and Concepts*[68]

A second tenet in the ASC charter involves searching the existing store of military and commercial standards to identify appropriate candidates for application. The preference would lean toward well-supported commercial standards (because of continuous development intensity), with the end goal being:

- *Scalability*—emphasizing upgrading and easy integration by modular design
- *Failure management*—embedded diagnostics plus selected redundancy
- *Unified networks*—with domain-contained timing simplifying integration, modification, and updating
- *Form, fit, and interface standards*—providing technology transparency

Perhaps no candidate commercial standards exist for unique Air Force applications. If so, DoD (open) standards are likely candidates.

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[68] Ibid., Slide 19.

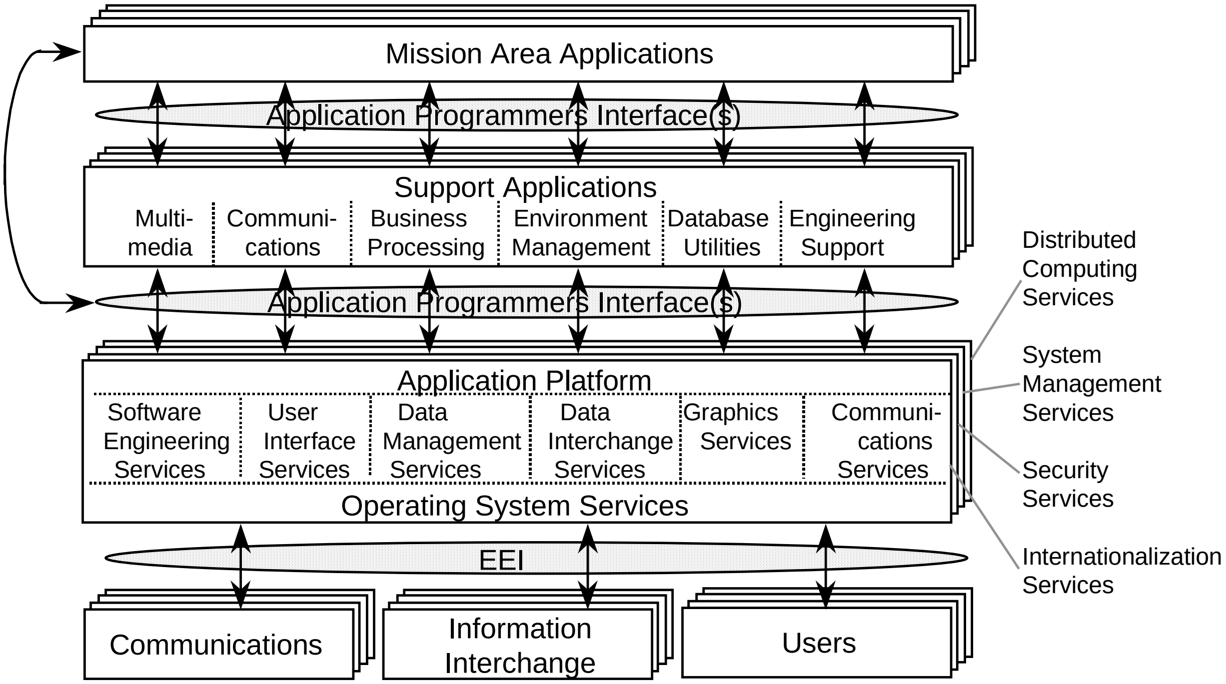

Figure G-15. *DoD Technical Reference Manual*[69]

Figure G-15 provides an example of an interface standard relating software entities. The model is meant for application in the common operating environment under the Defense Information Infrastructure (which defines an execution environment and a related set of system services accessible by software applications). The model establishes the interface relationships and the structure of interactions between applications and execution platforms.

The last ASC charter task is to provide the core set of architectural standards (to be levied by insertion in the acquisition template) on any new systems procurement. Figure G-16 shows an insightful approach to such architectural standards application–model satellite system that has:

- A vehicle/TT&C data bus with relatively low-rate (1-Mbps or less) data interchanges, and such potential interface standards as MIL-STD-1553/1773, Institute of Electrical and Electronics Engineers (IEEE) 1394, and RS 422.
- A payload data bus with medium-speed data rates (5 to 100 Mbps) and such potential interface standard candidates as MIL-STD-1773 or IEEE P1393 FODB.

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[69] Ibid., Slide 17.

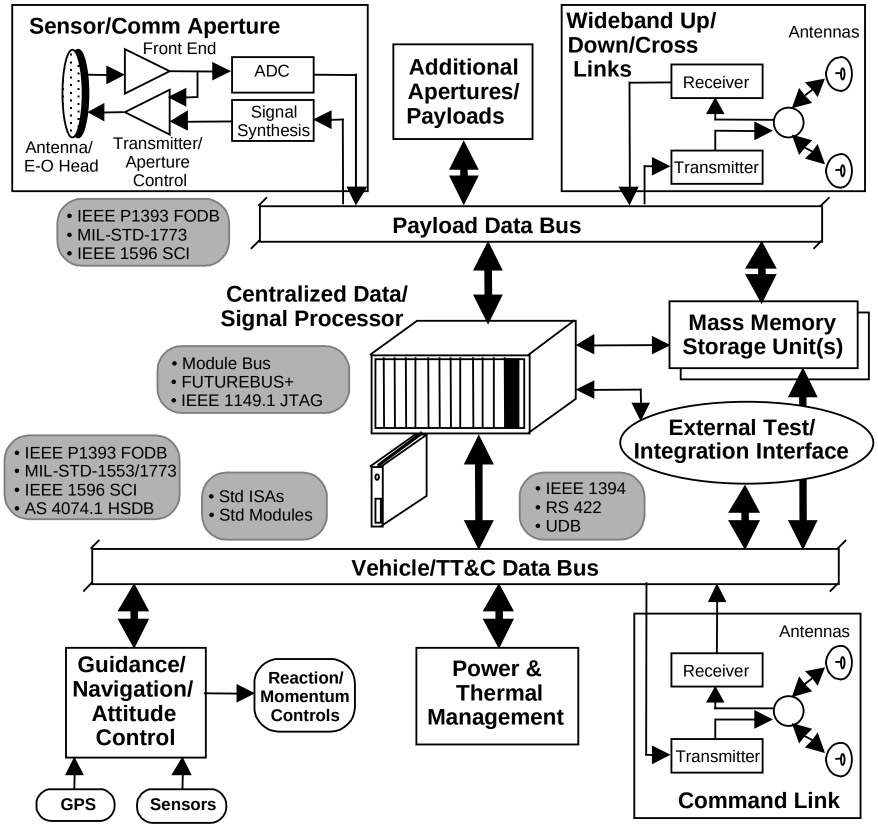

Figure G-16. *Proposed Satellite Architecture*[70]

Note that Figure G-16 shows no standards available or indicated for wideband up or down cross-links or command and telemetry links. The areas without standardization are where emphasis needs to be placed to yield the desirable capacity for interoperability among ground, air, and space assets.

6.7 Some Areas of Caution

In a presentation made on 22 June 1998 to the SAB Payloads Panel, Dr. John Doyle stated that "the overwhelmingly dominant source of risk in the discussed plans for the future of aerospace is the robust integration of 'systems of systems.'"[71]

There have been successes in developing highly complex systems (examples include the Internet, the Boeing 777, and the well-publicized very large scale integration design process), but there have also been spectacular failures. Examples include the California Department of Motor Vehicles computer and software upgrade, the recently abandoned Internal Revenue Service computer and software upgrade, the "slow roll" on the Federal Aviation Administration air traffic control system computer and software upgrade, and the Denver International Airport baggage handling system.

Successes have come as "the result of highly structured and systematic processes, with an almost obsessive attention to robustness."[72] Dr. Doyle cautions that while a close examination of the successes is

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[70] Ibid., Slide 26.

[71] John Doyle, Professor, Control and Dynamical Systems, California Institute of Technology, Mail Code 107-81, Pasadena, CA 91125, doyle@cds.caltech.edu.

[72] Ibid.

instructive, the insights are "of limited specific relevance to the kind of highly heterogeneous, nonlinear, dynamic, interconnected, integrated networks that are being assumed."[73] He recommends "extreme caution in expecting to generalize the methods in existing areas to the level of complexity envisioned in future military as well as civilian systems."[74]

The central issue "confounding a coherent picture of complex systems is that the theoretical and mathematical tools that are essential to study them are of unprecedented depth and sophistication, making them largely inaccessible to nonexperts."[75]

Dr. Doyle emphasizes that the "interplay between complexity and robustness" is "the most essential issue in complex systems, and the least well understood … Robustness and uncertainty management is becoming the central issue throughout technology yet we are investing relatively little in research directed at understanding how to make these systems robust and predictable."[76]

7.0 Roles for Small Satellites

Small satellites can create new capabilities, allowing existing missions to be better and more economically addressed and enabling new missions outside current requirements and plans.

7.1 Doing Existing Missions With Smaller Satellites

For small reductions in payload (including power supply and thermal management) at best spacecraft cost, volume and mass may decrease proportionately. But even proportional reductions are not always realized because spacecraft bus services (e.g., the launch vehicle interface and the communications system) and many ground support activities are often fixed-resource consumers—that is, they have a fairly inflexible cost per mission with respect to the individual system or activity. While there will be savings associated with these incremental reductions in mass, power, and physical dimension, these small changes will usually not allow exploitation of miniature satellite technology.

But at some threshold where the spacecraft would be considered small, these overhead elements can be reduced by more than their proportionality to the resource demands imposed by the spacecraft. When mission lifetime is short (3 years or less), financial risk is low and the system has a smaller number of components so that component reliability is not a design driver. This allows elimination of requirements for redundancy, which sharply decreases cost, mass, and complexity. In addition, designers can take advantage of components that are more modern and more capable and, although they may not be demonstrated to survive longer missions, further reduce complexity as well as cost, mass, volume, and power requirements.

Thus, an important application of small satellite technology is to perform existing missions more efficiently, leveraging the significant reductions in cost and resource requirements of their payloads to enable use of miniature satellite engineering, development, and operations methods. This can also be enabled by dividing a single large spacecraft into multiple small ones.

This evolutionary method must be approached with caution. The history of disruptive technologies is that they have often failed when they were introduced merely for a smooth transition, replication, or replacement of an existing technology. PCs were not successfully popularized as a replacement for mainframes, but, through innovation, small and much less capable computers particularly began filling important roles in widespread applications. Similarly, a small satellite will typically deliver less data and,

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[73] Ibid.
[74] Ibid.
[75] Ibid.
[76] Ibid.

less power to a payload, be built with poorer parts and procedures, and provide less performance overall per dollar, and on that metric will be criticized. The same can be said of an automobile compared with a school bus. Automobiles cost more per seat, burn much more gas per seat-mile, and require at least 25 percent of the passengers to be drivers, compared with 2.5 percent for a typical bus (i.e., the payload mass fraction for a school bus is much higher, and the overhead typically 10 times lower).

Nonetheless, preexisting requirements and plans and the potential to scale down to where microsatellite approaches may be applicable will drive application of newer spacecraft technologies to meet existing roles and requirements for which they may be less than optimally suited. This has potential to succeed in several areas as payloads become smaller and more resource efficient.

Communications and Remote-Sensing Applications

Despite some inherent inefficiencies, constellations of smaller satellites are replacing discrete larger spacecraft in some applications for communications and remote sensing. This is because factors other than cost efficiency for a specific, preexisting set of requirements are at work. These applications provide a means to highlight specific advantages of migrating to small spacecraft platforms.

Risk Mitigation. Risk is easier to manage with a constellation of many satellites via a series of launches. Motorola’s Iridium failure rate is 5 percent to 10 percent. The company states that it doesn’t care about the failures; in fact, the failure rate is built into the plan. While failure rate is comparable to larger spacecraft, the failures are not having major impacts on Iridium’s deployment. As an example, Iridium’s assembly line has never been stopped or slowed pending resolution of an on-orbit failure.

Launch Reliability and Cost. Launch to LEO is more reliable and cheaper than launch to GEO. A reliability of 85 percent is typical of GEO insertion (including the upper stage), but LEO insertions are 90 percent to 95 percent reliable—a 100 percent to 200 percent increase in reliability. Per-kilogram launch costs are about 10 times greater for GEO than for LEO, owing to the higher energy required for a GEO insertion.

Intrinsic Spacecraft Reliability Increases. Little LEOs, messaging satellites, are small enough that their intrinsic reliability is quite high, particularly against parts failures. They have fewer parts, so those parts fail much less often. These satellites are built with little or no redundancy, and it is notable that most redundancy on orbit is never used, and hence constitutes a major burden to larger systems.

Production-Based Cost Reduction and Reliability Enhancement. The larger number of spacecraft typical of small satellite systems provides economies from production learning curves, contributing to low cost. Despite plans to continue building some larger spacecraft over many years, the relentless progress of technology mandates changes in the spacecraft design with each subsequent block. Small satellites are built in blocks of typically ten times more satellites than large ones.

Frequent Upgrades. Commercial communications markets and military communications requirements and architectures are evolving rapidly, driven by the rapid pace of technology. By investing less in spacecraft lifetime and launching to lower-cost orbit we can upgrade or replace constellations quickly—on time scales as short as 5 years for current commercial systems.

New Services Enabled by Small Satellite Architectures. Though designed to replace previous conventional systems, a small satellite solution, typically in LEO, will enable some previously unavailable capabilities. For example, Iridium will enable continuous, real-time communication to LEO satellites without a worldwide network of ground stations and without requiring gain antennas on the small spacecraft resident-user terminals that point and track geostationary locations.

New Applications Opportunities. Many features that are claimed to be unique to LEO are in fact achievable as well from GEO satellites with spot beams. However, GEO satellites are inconvenient and impractical for these applications, just as it is possible but cumbersome to use a mainframe computer to do word processing or Web serving. If we were all interfacing to computers through only a small number of mainframes, the World Wide Web might exist, but it would have minimal impact.

Enhanced Capability. The following are a few of the potential net increases in system performance resulting from the use of small satellite architectures to accomplish existing missions:

- Frequency reuse.
- Hardening—A system composed of multiple spacecraft is harder to disable. Loss of any one, or even several, spacecraft may have no noticeable effect on system operations, resulting in only a marginal decrease in overall system throughput.
- Distributed apertures—Cooperating spacecraft over large distances, for example, can use a much higher resolution to find RF sources, or provide 3-D real-time imaging. They can also maintain a continuously on-station jamming presence to deny space utilities to an opponent. In addition, a small satellite constellation can provide continuous global coverage of weather patterns and artificial and natural surface features.

Just-in-Time Capability That Realizes Savings in On-Orbit Inventory. Small satellites are developed and built much more rapidly than large ones—currently on schedules of 1 to 2 years. Thus they may decrease the amount of capability that must be maintained on orbit, reducing costs of overcapacity.

Services Tailored to Specific Missions. Since the small satellite paradigm is to develop and launch on demand, we have the flexibility to tailor a spacecraft or group of spacecraft to highly mission- venue-specific demands. Different missions are characterized by differing service requirements, and they drive different design optimizations. Extensive ground operations in the field might require COMSATs that can simply extend the range of handheld communicators back to an over-the-horizon base. In remote sensing, different conflict venues have different requirements, for spectral coverage, resolution, revisit, and area of coverage.

Launch on Demand. The small satellite approach is to respond to emerging needs with a system tailored to a particular application's requirements with a relatively short-lifetime, low-cost system deployed only when needed.

7.2 New Applications Enabled by Small Satellites

The high cost of launch and the potential for improving reliability and quality of services provided, coupled with decreased net cost, make clear the value of reducing the size of spacecraft used to achieve current mission requirements. However, the greater the payoff, the greater the opportunity for significant change, and the greater the challenge in recognizing the new opportunities that small satellite technologies can introduce. A lesson from other disrupting technologies is that we have been unable to foresee their most significant applications. PCs preceded the Internet and World Wide Web by 25 years. Radio's largest audience is people riding in automobiles equipped with radios—a technology that didn't exist until at least 25 years after the inception of radio. The primary consumer applications of lasers as readers of compact discs and retail product price and inventory tags lagged the introduction of the laser also by about 25 years.

Thus, it is probably impossible to predict the ultimate or most significant applications of highly miniaturized space satellites, which are still in their infancy. Nonetheless, we can already foresee some applications that will be sufficient to greatly increase their importance in the next few years. These most valuable foreseeable new missions, enabled by microspacecraft, are largely not a part of today's requirements or plans. However, they have the potential to significantly increase overall effectiveness of deployed and virtually (or potentially) deployed space forces per invested resource compared with the current suite of missions, which are based mostly upon conventional spacecraft. A few new applications, not currently in the mainstream of planning, are treated below as examples of new ways of using space via microspace technology. This set of examples cannot be complete, and it may completely miss microspacecraft's most important future contributions. Nonetheless, the missions we can already foresee are significant and point toward the future importance of small satellites to the Air Force.

7.2.1 Inspector

Fundamental to the design of every space system is transportation—both to space from the ground and in space. Reliance on rocketry severely constrains the design and capabilities of every space system. Propulsion technology is mature. Hence microspacecraft, because of their very low mass, offer significant promise for the realization of highly maneuverable space systems deployed and operated at low cost.

For example, to rendezvous from an Eastern Range injection into LEO at an inclination of 28°, with another spacecraft at a 57° inclination at about the same altitude, requires a change in velocity of at least sin(57°-28°) x 7,700 m/s = 3,700 m/s. Assuming a bipropellant specific impulse of 310 seconds, a small spacecraft with a mass of 100 kg (including its propulsion system) would have to carry 240 kg of propellant for a total "wet" mass of 340 kg, and it would have a launch cost of $15 million to $25 million. However, a spacecraft of 1 kg dry mass would have a wet launch mass of only 3.4 kg—a payload with launch cost of essentially zero. It could replace ballast on nearly any launch. Thus the physics and economics of space transportation indicate that miniaturization will fundamentally enable missions that require great maneuverability.

Another distinguishing feature of microspacecraft is their low cost. As was often discussed during the Strategic Defense Initiative debate, a capability at least as expensive as the system it is meant to destroy or otherwise control has at best a tenuous rationale for its development. Microspacecraft are now being developed with costs of $10,000 to $100,000, making them three to five orders of magnitude less expensive, both to build and to launch, than many conventional space assets.

The most immediate application of the capability to cost much less than our own and our adversaries space assets and to be highly maneuverable is a class of applications referred to as "inspector missions."

7.2.1.1 Self-Inspection

One in 10 to 1 in 20 spacecraft will fail to operate nominally on deployment in orbit, or will suffer a significant on-orbit failure prematurely. When this occurs, several very costly and time-consuming activities begin. Numerous ground assets are redirected to gather data and help diagnose the anomaly. Teams are assembled on the ground to review available telemetry, the spacecraft design, the development and test history of the spacecraft, and any other data of possible relevance to the failure. Diagnosis of a nonfunctioning spacecraft is difficult and consumes the resources of the program personnel most highly in demand—those most knowledgeable about the system's history, engineering, and operation. And it is quite often an inconclusive exercise, leading to the launch of the next spacecraft in a series without confidence that the same anomaly will not recur. An example of such a situation was the failure of a commercial geosynchronous COMSAT that was not properly diagnosed until the same failure began to affect two other spacecraft in the same family. The total loss was nearly $1 billion.

A spacecraft with a mass of less than 10 kg and a cost of less than $100,000 could be colaunched with every major payload as a self-inspector. During the first few days after launch, the microspacecraft can optically observe deployment of the satellite from the launch vehicle and of sensors, antennas and solar panels on board the target spacecraft. Following the deployments, the "inspector" can sense the state of on-board central processing units (CPUs) by listening (in RF) for their clock signatures. In the same way it can detect receiver and transmitter operation—sensing, for example, the operation of a transmitter with a power amplifier or antenna failure.

Going a bit further, the inspector might be able to attempt simple fixes. It could transmit from very close range into a receive antenna to try to get new commands into a virtually deaf satellite. Similarly it could receive and rebroadcast signals from a satellite with no working power amplifier much more easily than trying to receive those signals from a massive dish on the ground. The microsatellite could do this continuously, rather than just when the satellite is in range of a ground station. In an extreme case the inspector could bump into a stuck hinge and try to unstick it.

It is worth repeating that the inspector, powerful as it might be, makes sense in this application only if its cost of development and deployment is no more than perhaps 1 percent of the cost of the target it observes. Otherwise it would be cheaper to allow satellites to fail, especially since even with the inspector only a fraction of on-orbit failures will be resolved. On the other hand, even if a problem cannot be fixed (for example, the large satellite is lost), information on the failure will help us avoid a subsequent related failure.

7.2.1.2 Protect Our Own Satellites

A major role of the U.S. Navy in its early years was not to engage enemies in war, but rather to protect commerce—especially from pirates. An emerging role of the U.S. Air Force, with the rapidly accelerating application of space for civilian commerce, may be space protection. (Note that this is a purely U.S. Air Force role. There is no potential for the Navy or Army to provide this role. It is in fact a pure "Space Force" role.) The elements of protection of both civilian and U.S. Government assets in space might include several elements.

Sentry. Satellites are not designed to watch for intruders for several reasons:

- They are not an environmental element that concern designers.
- Sentry duty requires looking into all directions, whereas most satellites are built to point toward their target (for example, a geosynchronous satellite wants to point its antennas at specific ground service regions and its solar panels at the sun; hence, it is not well adapted to scanning the 4π steradians all around it).
- The satellite carries no means of protecting itself even if an intruder is identified. A sentry can verify, and document via a downlink, the existence of an intruder. It can characterize the intruder, at least optically, and possibly profile its telemetry links and even on-board systems, much as the self-inspector remotely sensed the system's performance on board our own spacecraft. From these signatures, and from noting orbit position during control uplinks and data downlinks of the intruder, we may be able to identify the intruder's owner or operator.

Damage Assessment. Assume the sentry has detected an intruder, but we have no way to combat the intruder. Nonetheless, the sentry has created important value. If our spacecraft is suddenly disabled, without the sentry and damage assessment, we have no basis for claim against the intruder. We won't even know that a failure was due to intrusion, and, we might assume we had an on-board failure. This would drive our losses beyond just the spacecraft because we would spend additional resources trying to prevent another failure—maybe even delay deployment of key systems until the "flaw" is resolved. Another anonymous intruder could disable our next-generation spacecraft and thus seriously erode our confidence in our ability to build reliable spacecraft and dramatically slow deployment of critical systems.

Even if we somehow knew an intruder was the cause of a failure, we would lack several key elements of the story. To protect our systems in the future, we need:

- To know how the damage was affected (so that we can harden or otherwise preclude another successful attack).
- To know who committed the attack (so that diplomatic, economic, or technical means can be used to prevent future attacks).
- Most fundamentally, to document that an actual attack occurred. This could be via video of the attack, or at least by damage assessment of the spacecraft (before and after pictures), in case the attack is denied. The existence of a foreign spacecraft plus the occurrence of a failure, without damage assessment, is not valid evidence of an attack.

Spacecraft Servicing. Whether attacked by an intruder, by nature, or by an error in our own operations, the ability to effect a repair is invaluable. The economic value of a repair diminishes with the repair operation's complexity, but the marginal cost of enabling an inspector to do repair in addition to other roles is small for simple repairs, such as those discussed above (supplementing receiving or transmitting capability, or kicking a stuck mechanism). In the longer term, the existence of service inspectors will produce satellites that are built to be simply serviced, for example, by providing a simple means to swap out batteries or circuit cards or even discrete instrument boxes or optics. Ultimately a module could be developed for providing additional propellant either to a maneuvering orbital vehicle or to geosynchronous satellites.

Off-Board Services. Earlier it was mentioned that satellite complexity is increased by the need to track the sun for power, the ground station for a link, and sometimes also a remote-sensing target site. The inspector could be flown as an adjunct to another satellite to relieve one or more (via multiple microsatellites) of these sometimes disparate demands. The inspector could function as a near-field relay, receiving a very low-power omnidirectional RF or laser signal from the main satellite and transmitting it directionally to the ground. And at the same time, the inspector could receive ground uplinks and forward them with a similar low-power local RF or laser link to the satellite it is servicing.

Robotic Extravehicular Activities and Off-Board Services. A spacecraft has already been flown off the Shuttle by NASA to demonstrate the value of inspection of the Shuttle bay and potentially the International Space Station. The potential is now well recognized for inspector-type spacecraft to significantly decrease astronaut extravehicular activities for routine operations, such as vehicle surface and bay inspections and condition evaluations, and observation of the construction status of the International Space Station.

7.2.1.3 Inspect Non-U.S. Spacecraft

Besides the attributes already discussed (particularly the use of very lightweight spacecraft to enable the highest maneuverability at a cost low enough to make inspection economical), a microsatellite inspector has other advantages when used to inspect potentially unfriendly or adversarial spacecraft.

"Look" includes physical layout, listening for IF and other radio activities, processor activity, pointing direction, and time history of on-board activities.

Observability. Inspections will often be desirable before sufficient military and diplomatic justification for operations exists. In addition, we do not want to alert the potential adversary of the execution of these operations. A 1-kg satellite has minimal structure and RCS. After informal conversation with space tracking facilities, we believe that such a satellite would be observable only if measures were taken to increase its profile. This flexibility could be an advantage not only in allowing stealth inspection but also in revealing the inspector to substantiate a threat of interdiction.

Interfering With Operations. While a larger satellite might carry more power to disable a target satellite, a microsatellite or nanosatellite could keep the owner or operator of the target satellite from knowing that its decrease or lack of functionality is the result of intentional interdiction. This could create a false sense of security that another “random” outage won’t occur at critical times—but of course, it would. Also, fixing blame would be impossible, as would knowing exactly how the interdiction was affected. Most disabling techniques are enhanced by being close to the target satellite. Hence there is a tradeoff—as the inspector’s profile decreases, we can more closely approach the target without detection, and thus be more effective.

Two interdiction methods are illustrative. The inspector could shadow either the antennas or the solar panels. The latter would not require a metallic deployable, and might be very difficult to detect. Such shadowing is much easier from nearby, because the greater the distance from the satellite, the greater the propulsion requirements to remain co-orbital and in the right position. RF emissions might also be used. In addition to the orbital mechanics imperative to stay close by, the r^2 law also favors nearby emitters.

7.2.1.4 Conclusions Regarding the Inspector

The range of inspector missions contains many elements of Air Force space control, including

- Increasing reliability through close-range observations, active adaptation, and repair of some failures
- Enhancing capability of a range of spacecraft
- Protection of U.S. commercial and military space assets
- Projection of a credible threat to undermine or prevent space operations of opponents
- Ability to carry out the threat of denial of space asset operation

The inspector range of missions is exemplary of an emerging application not currently part of requirements and plans because it is enabled by the new technology of small satellites.

7.2.2 Debris Detection and Elimination

Debris is a constant threat to all space assets. A highly technical space-based force is extremely vulnerable to debris damage. Besides naturally present debris such as micrometeors, opposing forces could exploit debris to disable elements of the U.S. space force and commercial space commerce infrastructure. Debris detection and elimination is a complex mission requiring many elements, but the high maneuverability of small satellites makes them particularly well suited to debris control. Such maneuverable spacecraft could be used to rendezvous with debris and ultimately deorbit it. Note that it is possible to target debris with orbits most likely to intersect the trajectories of our satellites; for those special cases, sweeping with a highly maneuverable satellite built for low cost would be economically effective.

7.2.3 Suicide Missions

One class of space missions is accomplished only with the ultimate destruction of the spacecraft. Only with very low-cost spacecraft that have a small enough mass to make their launch costs similarly low do such missions make economic sense. This is an area in which low-cost small satellites are quite appropriate.

7.2.3.1 Smart Projectiles

A ballistic projectile, a "brilliant pebble," is either launched from the ground or deployed from orbit to hit land, sea, air, or space targets. Such a projectile could even be launched from an electromagnetic rail or ballistic gun. It must carry on-board propulsion and navigation, and in that sense is a small satellite that is destroyed when it is used. It must be of low mass to minimize launch cost, and it must cost very little to manufacture. Study has been conducted on satellites the size and shape of a hockey puck, which could accommodate a gun launch and in principle could incorporate the sensing, computing, and actuating facilities necessary to guide themselves to specific targets.

7.2.3.2 Ultra-LEO Remote Sensing

Observations from low-orbit altitudes are an existing method to enhance resolving power and sensitivity. Currently, spacecraft orbital lifetime is maintained mainly by use of HEOs and propulsion. An expendable (cheap) satellite can fly lower and would be less complex. One function of such a satellite is to map atmospheric density. This would aid planning of other ultra-LEOs (orbits so low that drag will cause reentry in less than 30 days) of remote-sensing satellites, and would greatly improve prediction of reentry points. The Air Force informed the SAB of the large uncertainties in entry point prediction, and the SAB understands that uncertainties in knowledge of atmospheric density are the major reason for our inability to accurately predict reentry points of LEO spacecraft and debris and to accurately hit reentry targets. A deorbited microsatellite sounder not long before the expected reentry event could eliminate most of this uncertainty. There is also a significant scientific return potential in periodic measurement of low-altitude atmospheric chemical constituency and thermodynamic state (i.e., temperature and density).

Actual remote-sensing observation from very low altitude may in some cases be more cost-effective without attempting to recover the ultra-LEO spacecraft, particularly for the lowest-altitude operations. In these cases a small, expendable spacecraft can be deployed for a single pass over a target of interest.

7.2.4 Data Relay Roles of Small Satellites

Conventional notions of space remote sensing use space-based active or passive instruments (the transducers), translating natural or stimulated emissions from the sensor into data. An alternative is to place sensors on or near the remote-sensing target (the transponder) and transmit, passively or actively, to the spacecraft. This alternative architecture has in fact been in use for decades. However, sensor readout cannot be called "remote sensing" until the number of sensors is very large, and hence their deployed cost, including readout cost, must be low. Such nanotechnology sensors already exist, but we lack the appropriate satellite systems for sensor readout necessary to exploit the local sensing and remote readout architecture.

7.2.4.1 Populous Sensors

The number of sensors to be read out can easily swamp the existing spacecraft capacity. Often, the spacecraft capabilities required for sensor readout are minimal, so the task can be handled by simple, small spacecraft. This frees more-capable assets to focus on sensors with special readout requirements.

Nanotechnology is beginning to provide the capability to distribute into the field thousands to millions of nanotransponders, which can be read out via interrogation from space. Most of these sensors will yield data that are either insignificant or redundant, though in some cases each sensor might constitute a pixel of a 2-D or 3-D array of data, e.g., for mapping the distribution of chemical agents in a plume. Current sensor readout architectures are ill suited to megasensor illumination and readouts. And the nanotechnology of today will almost certainly be obsolete in just a few years. Thus the best approach to the readout segment of the information pathway, the spacecraft, is a low-cost, low-lifetime ensemble (cluster or constellation) of simple spacecraft that are designed to be replaced on a time scale similar to the characteristic time for changes in the sensor technology—currently 1 or 2 years.

Readout via a network of LEO satellites can also alleviate the data overload potential of swarms of nanosensors. Each spacecraft can operate on the data received, forwarding only the processed information (for example, 3-D maps of scalar measures) to the network. This fits well into the distributed network architecture being proposed by the SAB.

7.2.4.2 Disadvantaged Sensors

Classically, disadvantaged sensors have been sensors placed in buildings or underground, often with poor antennas and weak transmitters to avoid detection. But the nanotechnology sensors now being developed will all be disadvantaged because of their very small size (millimeter-characteristic length) and lack of significant power. Small satellites, because of their low cost, can be deployed in larger numbers, and hence exploit LEOs that provide a 38-dB advantage in link margin, considering only the difference in path length from earth to LEO versus GEO. Of course some of this advantage can be mitigated by provision for very high-gain antennas at GEO, but this reduces coverage, requiring multiple antennas or satellites. A constellation of tens to hundreds in LEO can provide excellent datalinks to and from disadvantaged transponders, continuous coverage, low reconstitution cost, and large throughput, combined with resilience against an antisatellite weapon. But most important, the intrinsic link advantage of LEO or even ultra-LEO can enable new classes of sensors.

7.2.4.3 Broadcast

Even very small, low-cost (postage-stamp or smaller with a cost of pennies) sensors, which would be deployed in swarms, are able to be interrogated and receive instructions. This function may also swamp a small number of readout or control satellites. Frequency reuse is critical for addressing very large numbers of sensors, requiring either large numbers of on-board transmitters, each with its own spot beam, or numerous small satellites, each addressing a more-limited footprint.

7.2.5 Remote Sensing at Less Than $1 Million

Whether executed conventionally with spaceborne transponders or via a large number of deployed sensors read out by satellites, small spacecraft provide a means to perform remote-sensing missions at low cost. Launching on a space-available basis, mission-specific sensor flights have already been proposed with mission costs, including spacecraft, instrument, and ground operations, of less than $500,000 and with deployment times of under 1 year. Rather than attempting to provide a smorgasbord of remote sensors and data products that may only partially meet specific mission objectives, we can best exploit small satellites for custom applications. Here are some examples:

- Imagers placed into orbits optimized around current targets of interest
- Sensors optimized for the engagement region of interest (sea, desert, jungle, or urban)
- Supplements to existing sensor satellites to increase coverage frequency or to provide alternative sensors for a high-priority target
- Event-driven deployment of short-lived sensors (for example, liquid nitrogen or liquid hydrogen cooled). Similar rationale exists and has been exploited for supplementing communications capacity during conflicts.

7.3 Technology Enablers for Small Satellite Missions

Small satellites can create new capabilities, allowing existing missions to be better and more economically addressed and enabling new missions outside current requirements and plans.

Small satellite technology enablers divide naturally into two categories. Some address new capabilities that small satellites bring to space—for example, the larger number of satellites that can be deployed, their greater maneuvering capability, and their speed of development. Others are critical because of their cost savings potential.

7.3.1 Phase Coordination

While constellations and clusters of spacecraft can be effectively coordinated only through ground fusion of their communications links or data, cooperative operation among satellites brings several new capabilities to small satellites. An example is the use of multiple satellites fitted with radio receivers to do direction-finding of RF sources (including intentional but especially unintentional jammers). Some of these sources are very high frequency (VHF) and would require very large antenna arrays to accurately locate. However, if receivers on several satellites were phase coherent, the very large baseline (hundreds or thousands of kilometers) between receivers would provide very accurate position information. In addition, phase coherency among cooperative small satellites can be exploited to combine each satellite's aperture to create a very high-gain antenna system.

This capability can in principle be extended to higher frequencies and ultimately to light, but we are limited by the accuracy of timing (phase) information available among cooperating spacecraft. Current technology is to use GPS time signals, but GPS time precision limits coherency to VHF frequencies. This coherency capability could be improved to realize the potential of the distributed apertures that multiple small satellites provide. Besides GPS upgrades, possible means of increasing the quality of time information include synchronous laser links among satellites. Such links might be part of the intersatellite connectivity being recommended by the SAB. A common laser link can be exploited for synchronous detection only if we plan for it in the implementation phase.

The payoff of achieving phase coherency among satellites could be enormous. Not only could distributed networks of microsatellites accurately locate radio sources, but they could combine their receiving apertures to create very highly sensitive receiving arrays and very powerful transmitting arrays. These transmitting arrays could cooperatively downlink and uplink large amounts of data to primitive ground stations or directly to aircraft, and ultimately they could image very small and dim objects. Such systems could add a new capability in highly site-specific jamming as well as signal collection.

7.3.2 Deployable Apertures

The size of small satellites is becoming constrained not by the size of the satellite electronics but by three surface area–dependent functions: solar energy collection, radio transmission, and reception (antenna area) and in some cases an optical or other remote-sensing device aperture. As our ability to deploy large solar arrays grows, a fourth aperture will also become significant—radiators for dumping heat. Also significant is the size and mass of instrument and gravity gradient deployable booms. While there are ongoing programs in deployables, particularly deployable solar arrays, few if any focus on, nor are they necessarily applicable to, satellites with mass of 1 to 10 kg and a dimension of 10 cm. Besides the actual deployable structures, flexible photovoltaics and foldable optics, possibly with active alignment, may be helpful technologies applicable to both large and small spacecraft.

7.3.3 Navigation Suite

Regardless of the low fabrication and component costs achieved with miniaturization and modular approaches, navigation and attitude-control engineering remains a labor-intensive activity that is highly mission specific. A universal guidance, navigation, and control (GN&C) module could be developed around just two low-cost components. Sensing would rely on a suite of very low-cost star sensors. Typical microsatellite attitude determination does not require conventional star tracker accuracy.

A 256- by 256-pixel array with integral optics and processing, reduced to a single chip with a subcentimeter objective lens, is realizable with power consumption in milliwatts and mass in grams. Such a sensor could be deployed on each spacecraft face and would function in any orbit (LEO, geosynchronous transfer orbit [GTO], GEO, etc.). The actuator suite would consist of small-impulse bit microthrusters (tenths to hundredths of Newtons with a minimum pulse duration of 1 ms).

This combination—microthrusters plus microsunsensors—constitutes a complete, universal GN&C, assuming that the on-board processor closes the control loop. Use of a consistent sensor or actuator suite streamlines significantly the customization of pointing and tracking for individual mission requirements, currently a major cost element. In addition it provides the small satellites with a means to operate in any flight mode and any orbit—a capability not currently available in any satellite.

7.3.4 Nanotechnologies

The low cost of small spacecraft may limit the cost-effectiveness of large investments in technology from a return-on-investment point of view: the potential for savings is small given that the spacecraft cost presavings is already low. Historically, small satellites have instead leveraged commercial investment—in batteries, in electronics, in actuators, and in other specific technologies—focusing smaller investments on customizing these technologies for small satellite application. Given the large investments being made to develop nanotechnologies, the best leverage for Air Force dollars in this area might be in applications specific to spacecraft.

While many nanotechnology components are not going to be immediately practical, there are several near-term realizable silicon devices that the Air Force could develop with modest investment.

7.3.4.1 Nanotechnology Applications to GN&C

The integrated GN&C system, including a low-resolution star sensor and suite of small thrusters, is a candidate for high-level integration. The lens, focal plane, image processing, and star recognition algorithm execution including star maps are reducible to a single unit with dimensions on the order of 1 cm^2. While the thrust nozzles, valves, and propellant will be discrete, the GN&C module could include electronics for controlling the propulsion system and actuation of valves. It should also be equipped to power up and down star sensors to use those with appropriate aspects and protect those that may be earth or sun facing.

A GN&C module that relies solely on star sensing would be limited in bandwidth by the necessarily slow imaging and recognition process. However, like the pixel array and image recognition elements, current technology accelerometers could be integrated into such a chip to provide linear and angular acceleration, at very high bandwidths via integration rate and position information. Thus, the entire integrated system would incorporate lens, FPA, image storage and recognition, computing power for execution of closed-loop controller algorithms, thruster actuator commanding, and high-bandwidth linear and angular accelerometers.

7.3.4.2 Nanosensors

As discussed in the subsection “Data Relay Roles of Small Satellites,” nanotechnology on the ground, deployed as swarms of sensors, can enable microsatellites to do missions not possible even with the largest and most complex spacecraft. Such nanosensors might include chemical assay or radiation detection, coupled with passive or active transponders for communications with the interrogating microsatellite. These devices are already the subject of intense R&D efforts, and Air Force involvement could help focus and direct this powerful, largely private-sector investment into specific capabilities of particular significance to Air Force missions.

7.3.4.3 Highly Integrated Spacecraft

Encompassing the kernel of all spacecraft functions in a single circuit board is possible, but the technology is not currently available because the work of integration of subsystems into smaller packaging is not done. For example, while there exist commercial radios with capabilities similar to an on-board digital transponder that are compatible in size, mass, and power with a 1-kg class spacecraft, there has not been an adaptation of this technology specifically for a spacecraft radio set. Based on what has been accomplished in commercial S-band radios, modest investment could provide the small satellite community with a highly integrated receiver and transmitter with a combined mass of less than 100 grams, low power, and a footprint of a few square centimeters, at a cost in the range of $100.

This level of integration could also be accomplished in the other major subsystems: power control, input/output (both data and control of on-board systems), and data processing. These steps, neither expensive nor technically risky, would enable significant mass, power, and cost reduction of small satellites.

7.3.4.4 Small Momentum Wheel

While there is much focus on nanotechnology wheels for momentum storage, they have significant drawbacks. Nanotechnology wheels have not been perfected, and may not be for many years. Issues associated with current nanotechnology motors must be considered, including lifetime, repeatability, momentum management, torque noise, power requirements, and thermal control. Even when these formidable issues are eventually resolved, the resulting devices have insufficient momentum to stabilize spacecraft much larger than a silicon wafer. In the near future, however, small satellites will range from hundreds of grams to several kilograms. In the absence of the GN&C module discussed above, these spacecraft will require a momentum wheel. Target specifications will be a mass of 100 grams including wheel, housing, and control electronics, with a power of less than 100 mW including control electronics at nominal wheel speed.

7.3.4.5 Other Commercial off-the-Shelf Technologies

Small spacecraft are low cost and inexpensive to launch, traits that tend to favor shorter lifetimes. This makes them good platforms for introduction of COTS technologies. The cost of a failure is low, the lifetime requirement on orbit is short, and the smaller team can more adequately assess the suitability of a particular COTS component for the mission at hand. Rapid development time means that the COTS component life cycle will be longer than the development life cycle of the satellite, not necessarily true for conventional systems. The combination of a largely LEO application and a short on-orbit lifetime reduces radiation concerns, and reconstitution is a potential alternative to nuclear event survivability, at least for some missions.

Processors. Modern COTS processors benefit from more than reduced size, mass, and power requirements for enormous computing capacity. Less obvious is the benefit of investment in software development environments, including compilers and debuggers. These products themselves benefit from their wide use in the computer applications industries, so that mature products are efficient to use and largely bug-free. Thus, even with the budget to custom develop hardware and software, such systems would suffer from lack of sufficient field applications to make them competitive with COTS alternatives. Some features the Air Force might consider to increase the suitability of these COTS processors for small spacecraft are a stimulus to use materials and processes that are intrinsically radiation tolerant; provision for on-chip watchdog timers to provide local resets in case of software bugs or radiation-induced errors that halt processing; redundant storage of critical software (for example, the operating system); and enhanced error detection and correction. None of these features needs to be burdensome on the commercial part, and in fact could enhance reliability for all users.

Photovoltaics. Space photovoltaics cost about 1,000 times as much as terrestrial solar photovoltaics. For many small satellite missions, reduced lifetime and efficiency may be acceptably traded for cost savings of that magnitude.

Batteries. While numerous COTS nickel cadmium and lead-acid batteries have been flown, consumer electronics has moved on to nickel netal-hydride, Li-ion, and thin-film battery technologies. These are and should continue to be considered prime candidates for COTS application to small satellites. We recognize that few consumer devices operate above 14 volts (V), and many are focused on 3-, 5-, and 6-V systems. The 28-V standard is more appropriate for large spacecraft with a combination of larger power consumption and greater physical distances across which to transport electrical power. Small satellites will best leverage COTS components by focusing on buses of 6 V and below, with local direct current-to-direct current up-conversion if necessary.

Standards and Protocols. To the maximum extent possible, designs should use COTS backplanes, interfaces, communications protocols, and test standards. The test gear, software, and vendor support for very widespread products and development services make use of existing standards efficient overall, even if marginal cost is involved. This will become even more important as we move toward an integrated orbital network supporting data flow among different spacecraft developed in different environments and budgets at different times. An example is the communications protocol used for laser cross-links, a standard that is rapidly emerging in the commercial optical communications world and should be included in all spacecraft (big and small) design.

7.4 Mission-Specific Tailorship

Small satellites enable affordable spacecraft to be tailored to mission-specific needs when requirements are not technologically stressing.

Conventionally, space systems were developed by teams of experts at the few facilities built with large enough capital investments to accommodate the cleanliness, size, and special test facilities needed. But as spacecraft become much smaller and robust, little if any of this infrastructure must be available for satellite development, integration and testing. Small satellites usually do not require handling in a clean-room environment, they are built on a table top, and they are easily transportable to commercial or government test sites around the world. Thus small satellites can be built and operationally tested at the user's facility.

Moreover, much of the spacecraft complexity is absorbed into the spacecraft bus elements, which are becoming COTS items. The user should be capable of being, and should be trained to be, an active participant within the development process. The user's roles appropriately include configuring existing modules and operational modes to his or her specific applications, much as we select a suite of software packages (word processing, Internet browsing, e-mail) to provide the PC functionality we require.

7.4.1 Emphasis on In-House Development

Migration of satellite development activities from dedicated spacecraft centers toward the spacecraft user communities should be encouraged. Today, every engineer and operations person accepts the need to be computer literate, just as all who expect to travel much by car, are minimally automotive literate, and pilots are aircraft literate. Similarly, operations and development people at operational centers, such as Falcon, Kelly, and Lackland AFBs, who use satellites will need to become satellite literate. This is not a major hurdle. In professional courses, nontechnical students can begin producing top-level spacecraft designs and system architectures in 16 class-hours. This does not imply that an engineer can expect to build a computer, car, or aircraft, but that we know enough about how they work to greatly reduce reliance on technical support. For many spacecraft systems, architecture, development, deployment, and operations can be largely an in-house operation, with limited technical support from spacecraft specialists within the Air Force laboratory structure or industry.

To make this transition possible, the Air Force must focus on development of modules with well-defined, standardized interfaces. These modules can be relatively low level (for example, batteries and computers), or high level, as in the development of an extensible spacecraft kernel on a single circuit board. This kernel can then be built upon with solar panels, batteries, and sensors, just as we can build up a computing system from a CPU with a monitor, disk drives, a keyboard, and a modem.

An additional benefit of this migration toward in-house systems development through building up of modules is that it breaks the contractor-user or lab-user interface. At each such boundary, information is communicated only with some loss of fidelity. The resulting lack of complete understanding reduces system reliability and the robustness of the overall development program. These user-contractor relationships are a necessary evil for the development of complex systems, but they are less helpful as program size shrinks, and the benefits of their elimination need to be carefully considered.

7.4.2 Air Force Service and Infrastructure Roles of Microspace

Small satellites have become important for not only the missions they can carry out but also the opportunity they provide for education, infrastructure development, and testing.

7.4.2.1 Training

Small satellites are developed by small groups so that all the development team members have hands-on, systems-level experience in many aspects common to all spacecraft, including attitude control, parts selection, layout, launch vehicle interface, computing, communications, ground system operations, testing, and integration. These small groups provide an excellent laboratory for space savvy, which will be required of the leaders of tomorrow's space force.

The development life cycle of small satellites is typically 1 to 2 years. By telescoping the longer schedules and more complex management systems of larger spacecraft programs, small satellites help engineers, managers, and operations officers understand the development processes and stages common to virtually all aerospace systems.

7.4.2.2 Readiness, Reliability, and Robustness

We have seen in the Space Shuttle and several Russian launch systems that frequent, repetitive production and deployment is critical to maintenance of crew readiness and system reliability. Small satellite programs typically involve multiple spacecraft and limited on-orbit lifetimes. Both these factors create an environment rich in repetition, which not only offers opportunities for production streamlining, but maintains a team of developers, deployers, and users who understand the system's design and operation.

It is well understood that a cluster or constellation of tens to hundreds of satellites can be significantly more reliable than systems based on a very small number of larger spacecraft. The reasoning is that loss of one or two satellites results in a fractional degradation of system effectiveness. But repetitive development of spacecraft creates another type of robustness. Typically in custom development of one-of-a-kind systems, actual finished products cost more and are less capable than expected. As a system is repetitively built, integrated, tested, deployed, and operated, incremental improvements can be incorporated to gradually recover planned capabilities, extend to new capabilities, and drive down cost. Systems built later incorporate new features to eliminate previously existing but largely unexpected failure modes, so that the system becomes more reliable both as an engineered item and as an element of a mission's execution.

Beyond training, small satellites make excellent test items for system calibration, performance measurements, and active targets. (They can, for example, report on weapon effectiveness.) Small satellites have been successfully deployed to test missile detection (for example, CRO, 1990) and radar calibration (for example, NuSAT, approximately 1987). They also provide testbeds for new sensors (for example, ALEXIS, 1993).

7.4.3 Decision Level

A new and revolutionary technology (like satellites 40 years ago) requires coordination at the highest levels of an organization. By contrast, the purchase of off-the-shelf, low-cost items (for example, PCs and automobiles) need not be coordinated at such a high level and the decision to buy is organizationally closer to the user. This organizational truism has important implications for small spacecraft as they become less expensive and less complex.

Fielded Troop Applications

Tactical imaging has been discussed and debated since the first military demonstrations of miniature spacecraft in the early 1980s. It is often argued that such spacecraft are not efficient in terms of images returned or coverage or capability per dollar. However, the same can be said (but seldom is) of travel by automobile. Buses are much more efficient. However, these technical arguments are speculative. It is the battle commander's responsibility to allocate resources according to his or her best judgment, and if a small, low-cost, low-altitude reconnaissance satellite, no matter how inefficient compared with other satellites, is the most effective means to assess, for example, the placement of enemy troops and equipment, then deployment of the satellite may be appropriate. This capability to deploy spacecraft per local requirements would characterize a true integration of small, low-cost spacecraft into the force structure.

Another example of a fielded application of small satellites is VHF communications range extension. As a fielded force advances farther from the base camp, it eventually cannot directly communicate with VHF or higher-frequency communications links and must rely on spacecraft communications services. There is now only one option—to access major military communications systems, which may be difficult to access from the field, and may be otherwise engaged when needed. However, another option might be the use of commercial communications links, including Inmarsat or Iridium. However, these systems may be subject to jamming or be otherwise unavailable. A single, low-cost satellite can be launched as a reliable means of carrying messages both within the theater of operations and from the theater to any other location on earth (store-and-forward communications). This capability can also be exploited to readout sensors, for example, for determining the states of bridges and roadways, the passage of troops, or the presence or absence of electric power, RF energy, or other signatures of activity. The value of such simple, non–real time communications links was demonstrated in Desert Storm using Scout-launched 150-pound COMSATs as well as by the Navy GLOMR satellite as early as 1984.

7.5 Accommodation for Secondary Payloads

Current and emerging space transportation systems should routinely accommodate secondary payloads and multiple small satellites.

7.5.1 The Importance of Secondary Payload Accommodations to Small Satellites

The difference between the mass of our largest and smallest spacecraft is now four orders of magnitude. The smallest spacecraft weigh less than 10 percent of the mass margin carried by larger spacecraft near the end of their development process. Launch vehicles nominally fly ballast to balance any payload asymmetries and to ensure that the launch vehicle energy is properly matched to the actual payload mass to achieve the target orbit. The modern history of small satellites has been enabled largely through "piggybacking"—flying small satellites in place of some of the ballast. Most of these secondary payloads have flown on the Space Shuttle Get Away Special (now expanded in capability and known as Hitchhiker) and Ariane's Attached Payload Secondary Accommodation (ASAP) but also on the Long March (China) and various Russian rockets. Because these major launches are paid for by their primary payloads, the small satellite secondaries are flown generally for the cost of their mission-specific engineering, which is minimal because they comply with predetermined interfaces and envelopes, and for their safety certification. The availability of launch resources for payloads up to 150 kg and often as small as a few kilograms, and for costs typically in the range of $50,000 to $2 million, has catalyzed the development of spacecraft with similar costs. Academic and volunteer organizations have flown satellites with costs as low as $10,000, and commercially produced spacecraft have been piggybacked at costs around $1 million.

Without these secondary opportunities, the lowest-cost launch vehicle now available is the Pegasus, at roughly $16 million. It can sometimes be divided in half, providing a half-Pegasus launch for roughly $8 million. But those costs are prohibitive for the smallest, lowest-cost missions, and such opportunities are rare. Of more than 100 recent satellites under 100 kg, about 90 percent were launched as secondary payloads.

The low cost of secondary launch provides the means to space for some of our most important payloads. Without a low-cost launch, experimentation with new, relatively unproven technologies would be inhibited. The ability to rapidly fly a mission without proof of its efficiency, or time to ensure a successful outcome, is vital to research both on spacecraft engineering and responsiveness of spacecraft to the science and mission payloads we carry. Training functions of spacecraft would be impossible without low-cost piggyback opportunities. The risk advantage of launching numerous small satellites instead of a single larger one would partly disappear were it impossible to test-fly a prototype small satellite before committing to the launch of the constellation. Figure G-17 illustrates per-pound cost for primary and secondary launches.

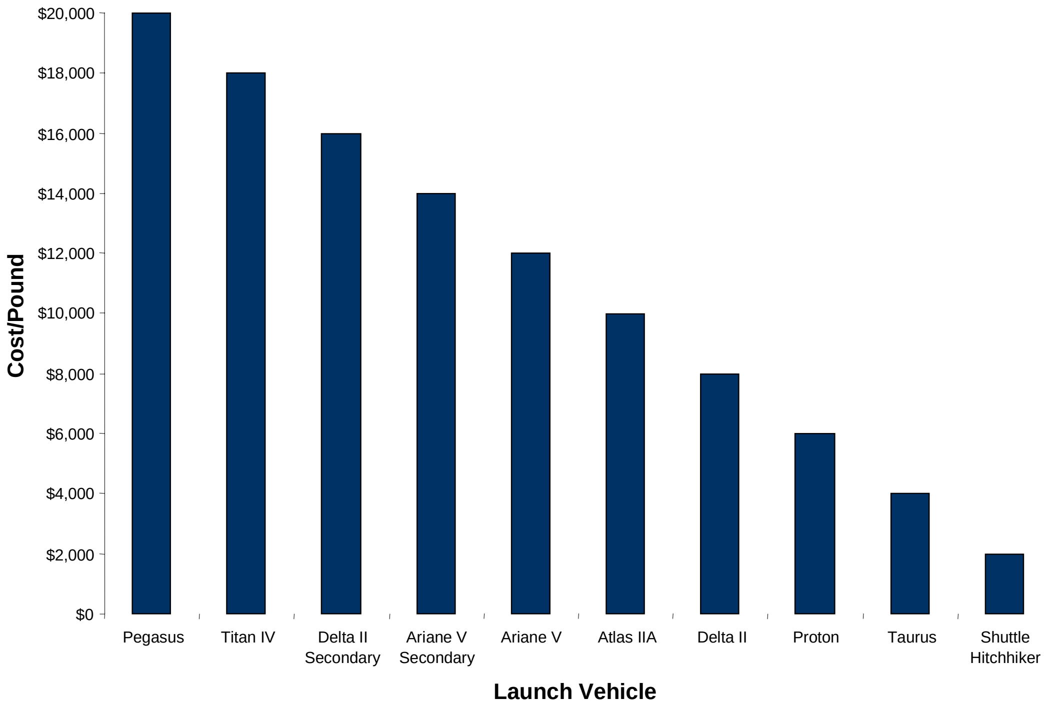

Figure G-17. *Piggyback vs. Primary per-Pound Launch Costs*

7.5.2 The Importance of Secondary Payload Accommodations to Large Launch Vehicles

It is clear to the microspace community that secondary accommodations are vital to the field. However, the importance of secondary launch accommodations to the major launch vehicle is seldom appreciated.

- The secondary payloads are often precursors to major payloads, and customer loyalty is created by flying secondaries.
- Revenues from secondaries are not always insignificant—they are highly profitable. Ariane, for example, must sometimes fly with up to 40 percent of its capacity unused, and has generated revenues over $10 million from combinations of secondary payloads, a significant increase in revenue at little increase in marginal cost.
- The engineering expended to accommodate secondaries is now providing benefits to launch vehicles being used to launch multiple COMSATs for constellations.
- Launch vehicles sometimes use the secondary accommodation to fly instrument packages to gain more information about the vehicle itself.
- Missions such as Pluto Fast Flyby, owing to their high change-in-velocity requirement, are only the size of a secondary payload, though they will fly as the primary. Thus, the secondary accommodation is in practice merely another primary launch vehicle accommodation, providing a broader product line to launch customers.
- Finally, secondary payloads provide a hedge against the failure of the primary spacecraft. If such a failure occurs, the existence of a successful secondary or group of piggybacked payloads provides positive public relations for the launch vehicle.

7.5.3 Secondary Payload Issues

The advantages of flying as a secondary payload are as follows:

- Low cost
- High reliability both in launch manifesting and launch success probability
- Frequent launch availability
- Benign launch environment
- For the Space Shuttle, opportunity to return to earth in case of ejector failure

However, there are also significant limitations to exploiting low-cost opportunities as secondaries, including the following:

- Low launch cost coupled with low launch mass may equate to high per-kilogram cost.
- Very early integration to the launch vehicle may lower reliability.
- Many available launches are to orbits that are undesirable for small satellites (for example, GTO).
- Large safety margins applied to secondaries mean that test environments may be cost drivers.
- The small launch envelopes and low mass that are available to secondaries often add cost to the small payload (for example, to use deployable arrays).
- Lack of supply elasticity—No additional major launch vehicles are launched because of an oversupply of attached payloads. Thus, major launch vehicle payload launch rates to desirable orbit constitute a cap on secondary launch resources.
- Manifesting uncertainty—Major launch vehicles retain the right to offload secondaries should the primary payload come in at a higher launch mass.

7.5.4 Steps the Air Force Can Take to Better Accommodate Small Satellites on Large Launch Vehicles

7.5.4.1 Mandate Secondary Accommodation on All Air Force Launches

Despite positive experiences of some launch vehicles, particularly the Shuttle and Ariane, with secondaries, other current and planned major launch vehicles have not invested in small satellite accommodations. Regardless of whether this business decision is in the best interest of the launch vehicles, it is not in the best interest of the Air Force. The Air Force purchases the entire payload mass, but because of the need for mass margin, typically 5 percent of that mass, and sometimes much more, is launched as ballast. It could have been additional Air Force payloads, or it could be commercial or science payloads, which would help ameliorate Air Force launch costs. We recommend a requirement to accommodate up to 5 percent of total launch vehicle throw weight to LEO as secondary payloads on all Air Force launch vehicles. The Air Force can “resell” this space at its cost to provide it. This reliable supply of secondary accommodation would be a tremendous motivator for the development and flight of small payloads.

7.5.4.2 Encourage Development of Space Maneuvering Capabilities

Even if the majority of a secondary payload mass allowance must be given over to propulsion systems, the Air Force should have the ability to achieve a desired orbit via piggyback pricing. Technologies required include the following:

- An integrated propulsion, GN&C module for piggyback payloads. There are commercial initiatives under way to build this capability, and the Air Force would need only to provide partial sponsorship or commitments to use these systems to help them to be realized and flight proven.
- Secondary payload rocket technology. Current designs use hydrazine, but suffer its drawbacks. Hydrazine systems are costly and impose significant safety and integration requirements on the satellite. Also, hydrazine performance is marginal. Hydroxylammonium nitrate-triethanolammonium nitrate or other hydrazine alternatives that might have improved performance and lower toxicity combined with good storability are desirable.
- Nontoxic propellants, so that the small payload, including propulsion, can be handled more informally, as is typical of most small, low-cost payloads.
- Technologies available in the near term. The secondary payload market need is immediate, and the suite of propulsion technologies available today, if modified for the small-payload maneuvering unit, have the basic desired capabilities. The Air Force should focus on realizing some capability today, with capability to evolve toward lower-cost, safer systems. Confidence in “new” chemistries, including hydrogen peroxide and H_2/O_2 rockets using water decomposition, is low because past efforts have not succeeded, despite promising appearance.

7.5.4.3 Develop a Small Expendable Launch Vehicle

The Air Force should consider development of a simple, present-technology (probably two-stage expendable) dedicated small launch vehicle, although it would not be a true secondary. The cost per pound, although it would likely be high compared with larger launch vehicles, would still be attractive, probably in the range of $2 million to launch 10 to 25 kg. Such a vehicle would provide a potentially covert, quick-launch capability to loft small satellites into LEO on demand. The ultrasmall launch vehicle (USLV) can be transported on a truck and, using a transporter-erector-launcher, could be assembled, launched, repacked, and removed for launch on demand without reliance on spaceports or airports. The USLV could also be launched from fixed sites and from ships at sea. This capability has, in part, been demonstrated by the Israeli Shavit launch vehicle.

7.5.4.4 Continue R&D on Gun Launchers

Small satellites have evolved into highly integrated systems that can be housed on a single circuit card of a diameter compatible with the kind of artillery most gun launchers plan to accommodate at first—typically 6 to 12 inches. These monolithic microsatellites should be able to withstand the 100,000-gram (1×10^6 times the acceleration due to gravity) environments typical of gun-launch orbital insertion. The extremely low recurring launch cost could revolutionize development of very small satellites and the systems capabilities that could be fielded in LEO.

7.6 Balance of Launch Cost Reduction and Spacecraft Miniaturization

There is an appropriate balance between investments in per-pound launch cost reduction and investments in spacecraft miniaturization.

7.6.1 Investing to Reduce Mission Cost

There are only two fundamental ways to reduce the cost of placing a particular capability in orbit: reducing per-pound launch cost and reducing the mass of the payload required on orbit. Both of these possibilities have received significant investment since the United States first flew into space in 1958. But it has been in the past 15 years that the emphasis of both government and commercial space has resulted in significant cost reduction. Over any window of time—the past 40 years, the past 15 years—the mass of the electronics, which constitute most of the space payload mass, has dramatically decreased, while launch costs have resisted significant change. In fact, it has been argued that the Shuttle is more expensive than the launch vehicles that preceded it, and even the Air Force's current attempt to lower launch costs, the Evolved Expendable Launch Vehicle, admits that order-of-magnitude cost decreases are not anticipated.

This is not unexpected. The basic technologies of materials for launch vehicles, the thermodynamic engines that propel them, and the chemical reactions that drive the engines have evolved only marginally in the past 40 years (see Figure G-18). In fact, most of the reduction in launch cost, if there has been any perceptible reduction, is attributable to the decreased mass of electronics in the GN&C systems they carry as part of their fixed mass.

By contrast, the past 30 years have seen a decrease by six orders of magnitude (a factor of 1 million) in the mass and power of information-processing electronics. These decreases have been exploited to reduce power requirements and hence the mass of power systems, and tremendously improved processing and information storage capacity has been used to reduce aperture requirements and other more slowly evolving capabilities. And just as launch vehicle materials have improved marginally, these same improvements have been incorporated into their satellite payloads so that even without the huge microelectronics revolution, satellite mass reductions would at least parallel savings in launch vehicle costs, which those marginal improvements have provided.

An emphasis on reducing launch vehicle cost without simultaneous attention to continuing decreases in payload mass may focus resources on the relatively stiffer solution, and downplay the enormous gains that may still be realized in payload mass reduction as a means to cut launch costs.

The discussion on swarms of active nanotechnology sensors further amplifies the potential of payload mass reduction in cutting launch cost. For some missions, rather than launching complex remote-sensing payloads into orbit, the spacecraft can be reduced to a bare minimum. Actual remote sensing can be performed by nanotechnology sensors that transpond to the microsatellite. This architectural option has the potential to reduce payloads for certain missions by orders of magnitude. This type of innovation plus continued rapid progress in space power production, low-mass deployable apertures, and low-power, low-mass electronics (including highly efficient RF systems) may indicate that the orders-of-magnitude decrease in payload mass of the past decades may be continuing.

7.6.2 Means to Reduce Launch Cost Via Payload Design

7.6.2.1 Large Payloads

Large launch vehicles are likely to continue to have lower per-kilogram launch costs than smaller ones because of the physics of the launch process and the fixed overhead that launch vehicles must bring to orbit. Thus while payloads shrink, we tend to continue to use the largest launch vehicles. This dichotomy has conventionally been addressed by piling more and more capabilities into the satellite to maintain its fixed, large mass. Thus the launch mass is constant, but the capability on orbit increases, sometimes dramatically.

Problems with this approach have reinvigorated the move to small satellites. These problems include prolonged development schedules and very high program costs, both of which make programs vulnerable to cancellation. Also, because technology and military requirements continue to accelerate the rate of change for satellites, the increasingly complex satellites we are flying have become unresponsive in this longer schedule.

The level of complexity of these large payloads challenges our ability to make them robust and has decreased their reliability. And in the PC world we have witnessed the power of providing technical capability in smaller sizes—to put capability in the hands of the ultimate user, to customize systems to individual user requirements, and to create new, unforeseen applications that weren't possible with mainframe architectures. Parallel forces are driving a migration to smaller payloads.

7.6.2.2 Clusters and Constellations

Alternatively, we can fly multiple small payloads to justify the launch of large, efficient launch vehicles. These are such constellations as Iridium and Teledesic. They launch smaller satellites that are more rapidly and economically developed, and focus on niche markets and applications (or geographical niches) in large fleets. This approach, like the large satellite solution, works when the mission justifies the launch of large numbers of identical satellites.

7.6.2.3 Attached and Secondary Payloads

Delta's proposed Pucksat and Ariane's ASAP and Spelda are means to fly large numbers of potentially unrelated small payloads to provide agglomeration into large launch vehicles. This approach is not likely to prevail because of the difficulties in coordinating unrelated payloads that must converge to a single launch site and date, and launch to a particular orbit.

7.6.2.4 Heterogeneous Payloads

One widespread trend that technology has brought to society is the increasing variation in product design. The smallest automobiles are still very small, but consumers still have very large vehicles available to them. Personal computers range in size from the same large boxes in which they were introduced 20 years ago down to palm-top. Similarly, all satellites were small in the 1950s and early 1960s, and in the 1970s they were predominantly large. Now we are transitioning to a world of greater diversity in spacecraft size, with a variation in technologies and management approaches suitable for each niche.

The cost minimization strategy must reflect this diversity, or risk becoming irrelevant to the Air Force customer as well as other space clients. Thus, minimum launch cost will be achieved by focusing on areas where payload or launch vehicle costs can be most dramatically reduced. Today this is mainly spacecraft and their instruments, and in the accommodation of a large range of spacecraft sizes on board each launch vehicle during each launch.

8.0 RADSAR—A Novel All-Weather Passive Surveillance Technology

The radiometric synthetic-aperture radiometer (RADSAR) is a passive microwave imaging concept. Slotted waveguide receivers are located on each of two parallel linear array antennas, referred to as "antenna elements." The relative phases of receivers along a single antenna may be varied, allowing compensation of structural imperfections and variation in the cross-scan direction of the beams. A point on the ground "sees" a change in the projected baseline as the antenna pair passes overhead (the baseline projected from the ground point varies with the cosine of the zenith angle to the antenna pair). Cross-scan resolution is inversely proportional to the length of the antennas. In-scan resolution is determined by the longest projected baseline, which is simply the separation of the antenna pairs. Both in- and cross-scan resolution improve as antenna frequency is increased.

Ground data collections were used with 6-foot slotted waveguide antennas separated by 6 feet and operating at X-band frequencies. Reduction of the collected data produced imagery with better than 1° angular resolution. A single receiver operated in a "triple superheterodyne" mode was fed by the antenna elements along the slotted waveguide.

Scaling up the RADSAR concept for space-based applications involves longer antenna lengths, greater antenna pair separations, and possibly higher operational frequencies. For example, the approximately 1° angular resolution used for the ground demonstration corresponds to a spatial resolution of about 1 m for a range of 60 m (representative of the ranges to scenes imaged during the ground demonstration). For a low-altitude, short-lived tactical orbit supporting on-demand battlefield surveillance (and possibly weather intelligence, given the 3-D imaging capability of the extended RADSAR concept), a 6-foot antenna in a 300-km orbit would correspond to a ground resolution element of about 5 km. Higher, more practical orbits provide larger ground footprints, suggesting that deployable, large antenna structures are required. Given the phasing potential of the antenna elements and the resulting capability to correct for imperfections of the supporting structure (as was done for the ground demonstration), the deployable option would appear tractable up to a maximum antenna size, yet to be determined. The scaling of the largest elements in both dimensions follows the same rule as for optical elements. If we use the Rayleigh criterion ($\theta = \lambda/D$) for the highest angular resolution, we can consider performance levels outlined in Table G-11.

Table G-11. *RADSAR Performance Levels*

Frequency (GHz)	*Wavelength (mm)*	*Antenna Length & Spacing (m)*	*GSD(m) (300-km Orbit)*	*GSD(m) (1,000-km Orbit)*
10	30	100	90	300
35	8.6	100	26	86
95	3.2	100	10	32
10	30	500	18	60
35	8.6	500	5	17
95	3.2	500	2	6

As the ground footprints in Table G-11 show, the weak point of this approach is the relatively coarse spatial resolution associated with these longer wavebands (relative to the IR, for example). The strong points of the space-based extension of this concept are: (1) near-hemispherical instantaneous FOVs, with in-scan spatial resolution improved over time as the projected interferometric baseline is scanned (by the passage of the satellite) over a fixed ground point; (2) a truly passive approach for which the spacecraft bus is lighter and less costly, and the sensor platform position is not revealed by a transmitter; and (3) the ability to penetrate clouds. The determination of altitudes to the bases of a battlefield in cloud cover approaches the "Holy Grail" of intelligence.

Recommendations

The Air Force should evaluate the extension of the RADSAR concept to 3-D capability (currently proprietary, and not discussed in detail here) in the context of cloud cover characterization. The technique should also have the capability to pinpoint ground transmitters operating within its frequency band.

9.0 Space Power Technologies

9.1 Electrical Power Systems[77, 78, 79]

Future spacecraft will require increased electric power to perform multiple functions. Fewer limitations in power permit spacecraft to have larger, more massive payload capability.

Currently, 20 to 30 percent of the mass of a satellite is devoted to its electric power system (EPS). The EPS mass is, in turn, distributed to energy storage (25 percent), solar-array structures (30 percent), power management and distribution (PMAD) electronics (10 to 20 percent), and PMAD cables and harnesses (25 to 30 percent).[80] For increased power efficiency, the EPS mass budget must move toward greater energy storage per conversion capability and reduced PMAD electronic and harness requirements.

Current energy storage programs include (in various stages of advancement) electrochemical energy storage (sodium sulfur, nickel hydrogen, Li-ion) and non-electrochemical storage (flywheel). These systems have PMAD power in the neighborhood of 10 W/kg, and the usable specific energy is less than 60 Whr/kg in LEO. The sodium sulfur battery has shown greater specific energy, but runs at excessive temperatures (approximately 300 °Celsius [C]), not lending itself as a promising technology for near-term space applications.

The Li-ion battery shows promise, except for its limited cycle life. In a typical LEO, the duty cycle is about 5,500 cycles per year. The 5- to 8-year life requirements of a satellite translate this into 30,000 to 48,000 cycles. In a typical GEO, the duty cycle of 100 cycles per year translates to a 10- to 15-year life requirement of 1,000 to 1,500 cycles. Thus, at present, the Li-ion battery must improve its life to exceed 50,000 cycles in order for it be useful in LEO applications.

Flywheel batteries have shown over 60 Whr/kg of usable specific energy, 90-percent depth of discharge, and potential long life. The flywheels can combine energy storage and attitude control in satellites, thereby achieving mass reduction for a combined system, perhaps by more than 80 percent. A technological challenge for the flywheels is to achieve long-life magnetic bearings.

9.2 Emerging Technologies

Advanced technologies being developed and tested are moving in the direction of lithium polymer electrolytes, advanced solar cells, thermal-to-electric energy conversion, and more efficient flywheels. The current SOA developments lead to an expectation of 40 to 60 W/kg PMAD, greater than 10 W/kg EPS, and 100 to 150 Whr/kg of energy storage in the near future. The fundamental technical challenge is to increase both the usable energy density and the cycle life.

9.2.1 Lithium Polymer Electrolyte

The cell uses a solid-state polymer electrolyte separator between a lithium-metal oxide cathode and a carbon/lithium anode. Expected energy storage is 154 to 176 Whr/kg of usable specific energy in GEO, 66 to 88 Whr/kg in LEO, and greater than 40 W/kg PMAD specific power. The mass saving from the GaAs/germanium (Ge) battery is expected to be more than 50 percent.

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[77] "Future Trends in Spacecraft Technology," briefing materials, AFRL.

[78] Dr. Dan T. Radzykewycz, Jr., "Energy Storage FTA Overview," briefing materials, AFRL.

[79] Dr. Kitt C. Reinhardt, "Power Generation and Distribution FTA TMR," briefing materials, AFRL.

[80] Data average from Milstar, DSCS III, DSP, GSP satellites.

9.2.2 Flywheels

More than 2,000 flight tests performed jointly by the Air Force and NASA have shown that magnetically suspended bearings can enable flywheels to attain a speed of 10,000 revolutions per minute. With continued advancement of this technology, the expected results are 117-Whr/kg of usable specific energy in GEO and 101 Whr/kg in LEO.

9.2.3 Solar Thermal Power Conversion[81]

The AFRL Space Vehicles Directorate is aggressively pursuing a dual path to produce highly efficient solar-array power for military missions in the next millennium. This will be achieved with a low-risk approach using conventional rigid solar-cell technology in a multijunction cell for high-power missions, and by a higher-risk yet high-payoff approach using thin-film solar cells for lower-power missions.

9.2.3.1 Multijunction Cells

High-efficiency multijunction cells based on rigid cell technology can achieve 35 percent efficiency by the 2003–2005 time frame, with specific powers of 140 to 200 W/kg. This technology can enable very high-power satellites exceeding 25 kW needed for future SBR and directed-energy missions. These projections are based upon single-junction GaAs devices that today have efficiencies exceeding 21 percent, three-junction $GaInP_2$/GaAs/Ge ManTech devices of 24 percent efficiency to be in production by 2001, and a four-junction GaAlP/GaAs/InGaAsN/Ge design for 40 percent efficiency patented jointly between AFRL and Sandia National Laboratories. These rigid cells are projected to achieve specific powers of 200 W/kg, reducing weight and launch costs for future missions to $300 per watt.

9.2.3.2 Thin-Film Solar Cells

In order to achieve specific powers exceeding 400 W/kg at lower costs, AFRL is also developing multijunction thin-film solar cells. This technology will greatly reduce launch costs and is envisioned for smaller satellites (mini- and microsatellites) as well as for UAVs. Projections indicate that a 15 percent efficient cell is achievable by 2001 with specific powers near 200 W/kg, and greater than 30 percent efficiency in reachable in the 2005–2010 time frame with specific powers over 400 W/kg using high-temperature processes. The development of a lightweight, flexible substrate that is thermally stable at above 550°C is a key technical challenge for these cells. An innovative ultralight pantograph support structure is under development to deploy these advanced solar arrays. Roll-to-roll thin-film processes will also reduce solar-array costs by an order of magnitude as compared to the costs of rigid cell technology.

9.2.3.3 Rainbow Solar Arrays and Thermal Radiators[82]

Vertical arrays that stack three to four cell types have shown efficiencies of 28 to 35 percent, but the currents and voltages of the different cells are difficult to match since all cell types must be the same physical size but produce different voltages. In addition, they cannot be used with high concentration ratios because of heat dissipation limits since the area for heat rejection is unchanged from single-cell arrays. The “rainbow” technique, conceived by Dr. Wade Blocker of Aerospace Corporation in 1976 and investigated by Dr. Ivan Bekey splits the incoming solar spectrum into many portions and impresses each portion on a separate cell, which has a bandgap that is tailored to the incoming narrow range of wavelengths. Since each type of cell may have a different size, shape, and number in a series, this technique attains a better current and voltage match than is possible by vertically stacked cells. Thus higher efficiencies for the same number of spectral regions is achieved. Additionally, this technique

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[81] Dr. Alok Das, “Solar Thermal Power Conversion Technologies at the Air Force Research Laboratory,” briefing materials, AFRL.

[82] Dr. Ivan Bekey, conversation.

minimizes the heat load on each cell since most of the spectrum is diverted elsewhere, and each cell has its own area for thermal dissipation. Thus, high concentration ratios can be used while maintaining low cell temperatures.

The solar array resulting from all these features has a theoretical efficiency approaching 60 percent using many cell types. Experiments with four cell types have shown 52 percent efficiency, which is expected to exceed 56 percent with a larger number of cell types and modest concentration. The cell types required exist, being principally gallium indium phosphide and aluminum GaAs (various dopings), silicon carbide, and silicon. These are real cells, though some types have not yet been engineered for larger quantities.

The figure of merit of the "rainbow" technique is calculated to attain close to a factor-of-two improvement over vertically stacked cells (both with four cells), and a factor-of-four improvement over silicon planar arrays.

Annex to Appendix G

Acronyms and Abbreviations

λ	Wavelength (mathematical symbol)
μflick	$\mu W/cm^2 \cdot sr \cdot \mu m$ ($\mu = 10^{-6}$, sr = steradian)
μm	Micrometers
μrad	Microradian
1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional
ABL	Airborne Laser
ACC	Air Combat Command
ACeS	Asia Cellular Satellite System
ADC	Analog-to-Digital Converter
AEHF	Advanced Extremely High Frequency
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
ALEXIS	Array of Low-Energy X-Ray Imaging Sensors
AMTI	Airborne Moving-Target Indication
APMT	Asia Pacific Mobile Telecommunications
ASAP	Attached Payload Secondary Accommodation
ASC	Architectural Standards Committee
ASIC	Application-Specific Integrated Circuit
AWACS	Airborne Warning and Control System
AWS	Advanced Wideband Service
BMD	Ballistic Missile Defense
C	Celsius
C/A	Coarse Acquisition
C^3I	Command, Control, Communications, and Intelligence
C-band	Frequency of 4 to 8 GHz
CDMA	Code Division Multiple Access
CFLOS	Cloud-Free Line-of-Sight
cm	Centimeter
CMOS	Complementary Metal on Silicon
COMSAT	Communication Satellite
CONOPS	Concept of Operations
CONUS	Continental United States
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CRD	Capstone Requirements Document
CW	Continuous Wave
DAMA	Demand Assignment Multiple Access
DARPA	Defense Advanced Research Projects Agency
DAS	Detector Angular Subtense
dB	Decibels
DISA	Defense Information Systems Agency
DISN	Defense Information Systems Network
DoD	Department of Defense

DoE	Department of Energy
DoT	Department of Transportation
DSCS	Defense Satellite Communications System
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Optical Fiber Amplifier
EHF	Extremely High Frequency (30 to 300 GHz)
EO	Electro-Optical
epi	Epitaxial Deposition
EPS	Electric Power System
ERASER	Enhanced Recognition and Sensing Ladar
ERDB	Evolving Requirements Database
ESC	Electronic Systems Center
FDMA	Frequency Division Multiple Access
FOV	Field of View
FPA	Focal Plane Array
GaAs	Gallium Arsenide
GBL	Ground-Based Laser
Gbps	Gigabits per Second
GBS	Global Broadcast System
Ge	Germanium
GEO	Geosynchronous Earth Orbit
GHz	Gigahertz
GMTI	Ground Moving-Target Indication
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
GSD	Ground Sample Distance
GTO	Geosynchronous Transfer Orbit
HEO	Highly Elliptical Orbit
HF	Hydrogen Fluoride
ICO	International Communications Organization
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IM	Intensity Modulation
IOC	Initial Operational Capability
IPT	Integrated Product Team
IR	Infrared
IRT	Independent Review Team
J	Joules
JCS	Joint Chiefs of Staff
JPL	Jet Propulsion Laboratory
JPO	Joint (Service) Program Office
JointSTARS	Joint Surveillance, Target, and Attack Radar System
K	Degrees Kelvin
Ka-band	Frequency of 25 to 40 GHz
kbps	Kilobits per Second
kg	Kilogram
km	Kilometer
Ku-band	Frequency of 12 to 18 GHz
kW	Kilowatt
kWhr	Kilowatt Hour
L1	GPS band centered on frequency of 1575.42 MHz

L2	GPS band centered on frequency of 1227.6 MHz
Ladar	Laser Radar
L-band	Frequency of 1 to 2 GHz
lbs	Pounds
LDR	Low Data Rate
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
Li-ion	Lithium-Ion
LLNL	Lawrence Livermore National Laboratory
LNA	Low-Noise Amplifier
LPD	Low Probability of Detection
LPI	Low Probability of Intercept
LWIR	Long-Wavelength Infrared
m	Meter
mm	Millimeter
Mbps	Megabits per Second
MCT	Mercury Cadmium Telluride
MDR	Medium Data Rate
MEM	Micro-Electromechanical
MEO	Medium Earth Orbit
MHz	Megahertz
MILSATCOM	Military Satellite Communications
MIL-STD	Military Standard
MMIC	Monolithic Microwave Integrated Circuit
MRAAS	MTI Requirements Analysis Study
MSS	Mobile Satellite System
MTI	Moving-Target Indication
MWIR	Mid-Wavelength Infrared
N-Able	Non-Proliferation Airborne Lidar Experiment
Nadir	Opposite the zenith. That point in the celestial sphere directly opposite to the zenith, and directly below the observer.
NASA	National Aeronautics and Space Administration
NAVSTAR	Original name for the GPS program
Nd	Neodymium
NESR	Noise-Equivalent Spectral Radiance
nm	Nanometer
NRE	Nonrecurring Engineering
NRO	National Reconnaissance Office
OASD	Office of the Assistant Secretary of Defense
OPD	Optical Path Difference
OPR	Office of Primary Responsibility
P	Precision
PC	Personal Computer
PCC	Payload Control Center
PCL	Passive Coherent Location
PL	Phillips Lab
PMAD	Power Management and Distribution
ps	Picosecond
PWB	Printed Wiring Board
QPSK	Quadrature Phase Shift Keying
R	Range (mathematical symbol)

R&D	Research and Development
RADSAR	Radiometric Synthetic Aperture Radiometer
RCS	Radar Cross Section
RF	Radio Frequency
rpm	Revolutions Per Minute
RS	Remote Sensing
RV	Reentry Vehicle
s	Second
S&TW	Surveillance and Threat Warning
SA	Selective Availability
SAB	Air Force Scientific Advisory Board
SAR	Synthetic-Aperture Radar
SATCOM	Satellite Communications
S-band	Frequency of 2 to 4 GHz
SBIRS	Space-Based Infrared System
SBL	Space-Based Laser
SBR	Space-Based Radar
SCR	Signal-to-Clutter Ratio
SiGe	Silicon Germanium
SMC	Space and Missile Systems Center
SNR	Signal-to-Noise Ratio
SOA	State-of-the-Art
SOR	Starfire Optical Range, Kirtland AFB, New Mexico
SOSA	System-of-Systems Architecture
SPEAR	Space Electronically Agile Radar
SSPA	Solid-State Power Amplifier
STU-III	Secure Terminal Unit (Model III)
TDMA	Time Division Multiple Access
T/R	Transmit/Receive
T1	1.544 Mbps Communications Line
TDI	Time Delay and Integration
TDRSS	Tracking and Data Relay Satellite System
TE	Thermoelectric
TRAM	Transmit/Receive Antenna Module
TT&C	Telemetry, Tracking, and Control
UAV	Unmanned Aerial Vehicle
UFO	UHF Follow-On
UHF	Ultrahigh Frequency (From 300 MHz to 3 GHz)
USA	United States Army
USAF	United States Air Force
USLV	Ultra-Small Launch Vehicle
USN	United States Navy
V	Volt
V-band	Frequency of 40 to 75 GHz
VCSEL	Vertical Cavity Surface-Emitting Laser
VHF	Very High Frequency (From 30 to 300 MHz)
VLWIR	Very-Long-Wavelength Infrared
W	Watt
WAS	Wide Area Surveillance
WIN	Worldwide Information Network
Whr	Watt-hour

X-band	Frequency of 8 to 12 GHz
XDR	Extended Data Rate (New protocol for Advanced EHF)
Yb	Ytterbium

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Appendix H

Vehicles and Lift

1.0 Charter Summary

The Vehicles and Lift appendix addresses current issues and provides recommendations dealing with space launch vehicles, launch infrastructure, space operations vehicles, spacecraft buses, and potential high-leverage technology areas.

Lift vehicles are analyzed from the standpoint of metrics such as cost per unit weight to orbit, turnaround time, robustness, responsiveness, and desired level of commercial involvement. Both reusable and expendable launch vehicles (RLVs and ELVs) are considered, with emphasis on the lift needs of Air Force systems and their differences from current and projected commercial lift requirements. The launch infrastructure portion, dealing primarily with launch pads and ranges, focuses on the increasing need to modernize the facilities and the organizational structure to support the projected growth in commercial launches. The Aerospace Operations Vehicle (AOV), based on a military concept of operations (CONOPS), is presented. Spacecraft buses are addressed in terms of the adaptation of commercially available buses for unique military requirements to minimize cost and cycle time. Radiation susceptibility of commercial low earth orbit (LEO) and geostationary earth orbit (GEO) buses is described. The appendix concludes by describing high-leverage technologies that can revolutionize the approach to spacecraft and launch vehicle structures and propulsion, and satellite power generation.

1.1 Vehicles and Lift Panel Membership

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2.0 Summary Findings and Recommendations

The following subsections summarize the key findings and recommendations by the Vehicles and Lift Panel. The underlying theme for many of the recommendations is to reduce launch and satellite cost through acquisition reform—that is, to take advantage of industry's ability to design, manufacture, launch, and operate space systems faster and more cheaply than the Government. This "buy commercial" approach must be augmented by continued government investment to assure military capability and access to space.

2.1 Launch Vehicles

Findings:

- The Evolved Expendable Launch Vehicle (EELV) provides assured access and cost reduction.
- Commercial space business is growing exponentially and offers large-volume opportunities for continued cost reduction.
- RLVs will provide substantial improvements in dollars per pound to orbit, provided the commercial space business continues to grow and technology barriers are overcome.

Recommendations:

- Support EELV.
- Focus Air Force Research Laboratory (AFRL) research, particularly in areas of materials and propulsion, to reduce launch vehicle and operational costs and ensure reliability.
- Develop the skill base to buy commercial launch services instead of buying launch vehicles.

- Coordinate with the National Aeronautics and Space Administration (NASA) to support RLV technologies.

2.2 Launch Infrastructure

Findings:

- Launch facilities are key to assured access.
- Launch facility operations are costly and increasingly unreliable. Facility operations costs were more than $500 million in FY 98, and the frequency of launch delays has tripled in the past 2 years.
- The commercial launch rate increasingly dominates launch infrastructure requirements.
- Current plans and funding are inadequate.

Recommendations:

- Modernize ranges to support the projected increase in commercial activity and to adapt to the changing role of the ranges in a more commercial launch environment. Specific areas to address are reducing operations and maintenance (O&M) costs, transitioning to a “space-based range,” and closing down range assets, to improve reliability and to support increasing commercial requirements. Use an omnibus contract approach (like United Space Alliance) to generate committed savings that can support modernization.
- Plan to transfer launch infrastructure responsibility: transfer safety to an appropriate Federal agency; transfer operations to a National Space Authority.

2.3 Concept—Aerospace Operations Vehicle System

Findings:

- An AOV system enables revolutionary capabilities:
  - Global hypersonic recce or strike,
  - Rapid emplacement of lethal and nonlethal space control,
  - Rapid constellation replenishment, and
  - Retrieval and servicing on orbit.
- Two-stage-to-orbit (TSTO) technology risk is lower than that of single stage to orbit (SSTO).
- SSTO has major operational advantages, but is higher risk and longer term.

Recommendations:

- Develop operational concepts via a Space Maneuvering Vehicle (SMV) near-term demonstration (approximately $35 million per year for 4 years).
- Develop a follow-on AOV concept, plan, and roadmap.
- AFRL should coordinate RLV-supporting technologies with NASA.

2.4 Spacecraft Buses

Findings:

- The Air Force can realize substantial cost savings and shorter cycle times by the prudent use of commercial buying practices.
- The increased demands for data compression, on-board processing, autonomous operation, and higher pointing accuracy require increased computational capability.

Recommendations:

- Adapt commercial spacecraft buses to meet military needs where practical.
- Work with industry to establish a minimum set of unique bus requirements beyond standard commercial practices.
- Focus near- and medium-term technology development to improve energy storage density and the efficiency of solar cell power generation.
- Invest in radiation-hardened processors and memory storage devices.

2.5 High-Leverage Techniques and Technologies

Finding:

- Investments in high-payoff technology areas can offer revolutionary advancements in launch vehicles and spacecraft for the next 20 years.

Recommendation:

- Show Air Force commitment to aerospace leadership by focusing technology base resources on key future space needs. Some examples of high-payoff areas are highlighted in Section 8.7.

3.0 Expendable Launch Vehicles

3.1 Background—Definitions and History

ELVs are still the mainstay of the Air Force's access to space. The *Challenger* Space Shuttle tragedy forcefully brought home the need to assure multiple paths to space. It also illustrated the importance of having an effective national policy that encourages multiple launch-vehicle suppliers. In the aftermath of the *Challenger* accident, many satellites, designed for the Shuttle's cargo bay, were awaiting launch with no expendable vehicles in the U.S. inventory capable of meeting their design requirements for launch into space. This drove a large part of the commercial satellite business offshore.

Since that time, government and industry have developed a group of ELVs capable of meeting the requirement for U.S. commercial and government access to space, independent of the Space Shuttle. A sampling of the launch weight capabilities of U.S. vehicles and several international competitors is shown in Table H-1.

Table H-1. *Typical U.S. and International Expendable Launch Vehicles and Capabilities*

Launch Vehicle	*Pounds to LEO*	*Pounds to GTO*[1]
Atlas IIAS	19,050	8,450
Atlas IIIA	19,050	8,940
Atlas IIIB	23,730	9,920
Delta II	11,330	4,120
Delta III	18,280	8,400
Titan II	4,200	—
Titan IV	48,000	19,000
Ariane 44L	15,430	10,625
Long March-2E	20,240	7,430
Ariane 5	39,680	14,990
Proton	46,000	10,584
Zenit 2	30,300	—

[1] Geostationary Transfer Orbit

A second recent change in the launch environment is the increased number of commercial satellites requiring launch services. This increased activity was unexpected, even 4 years ago. Launch data for the past 2 years and data for 1998, including actual launches through June 1998 and scheduled launches through December 1998, are shown in Table H-2.

Table H-2. *Launch Activity From the Eastern and Western Ranges, 1996–1998*

	1996		*1997*		*1998*	
	Western	*Eastern*	*Western*	*Eastern*	*Western*	*Eastern*
NASA[1]	3	11	2	11	7	7
DoD[2]	5	3	7	7	7	4
Comm[3]	1	9	8	7	7	21
Ballistic[4]	6	0	5	0	12	0
Totals	15	23	22	25	33	32

[1] Includes planetary and Shuttle missions
[2] Includes all government launches, including National Reconnaissance Office
[3] Includes all commercial launches
[4] Includes Peacekeeper and Minuteman launches

Forecasts of the number of future space launches have underestimated demand. As shown in Table H-2, the commercial space business is expanding rapidly; commercial launches projected for 1998 and beyond dominate the world launch market and are the majority of the launches from the U.S. Eastern and Western Ranges (ER and WR). This increased launch rate is reducing the cost of launching commercial satellites into space. However, increased demand for launch services may create a problem with the ranges: we believe that, in its present form, the U.S. ER and WR launch infrastructure is not capable of achieving or sustaining projected commercial launch rates. This problem is discussed in Section 4.0 of this appendix.

In addition to increased demand for launch services, the satellite launch market itself is changing; for example, some launches involve multiple satellites on the same booster. Because the market is dynamic, future launch vehicle lift requirements are difficult to predict. However, there appears to be a trend toward heavier launch vehicle payload requirements. For instance, GEO communication satellites are getting larger, and launching multiple payloads is becoming more popular, especially for small-to-medium LEO communication constellations.

The commercially dominated market is placing pressure on commercial suppliers to reduce the cost to place satellites into orbit. Competition from international launch services, such as the European Ariane and the Chinese Long March, is reducing the price of launch services.

3.2 Cost Goals and System Improvements

There are distinct differences between commercial requirements and government needs. For instance, both government and commercial services demand highly reliable systems; however, commercial services also demand lower cost and can get it by simply selecting from among a group of international suppliers. Commercial enterprises have global customers, competitors and partners, as well as international launch service suppliers, whereas the ratio of the military market for launch services to the total demand is much smaller. The military launch requirements are governed by legislation and well-defined procedures that add cost, as does the ability to "launch on demand."

Because of the sensitive and proprietary nature of launch vehicle cost data, only rough estimates can be made. A typical split for launch costs is 60 percent for the launch vehicle, 10 percent for launch operations, 10 percent for mission integration, 10 percent for avionics, and 10 percent for program management and systems integration. While these numbers are rough, they illustrate that the cost of the launch is an integrated cost and is more than just the cost of hardware. Solutions for cost reduction must address this wide range of factors, including operations.

Expendable vehicles, with today's technology, have a "floor," or lowest cost achievable, of approximately $1,500 to $2,000 per pound to LEO. This compares to current prices of about $5,000 per pound. The EELV is targeted at $2,000 per pound to LEO and about $6,000 per pound to geostationary transfer orbit (GTO). After the EELV system is fully operational, it may be possible to reduce the costs to $1,500 per pound. (The EELV program is discussed later, in Section 3.4.)

3.3 Technologies to Support Reduced ELV Cost

Vehicle design, reliability, and cost are driven by the propulsion system. Engine improvements, including reduced manufacturing cost and improved interfaces between the engine and ground test and monitoring have reduced the cost of vehicles markedly. Still, we need better engines. For instance, the RL-10 upper-stage engine is a 1961 design. It is reliable, but it is old technology. New materials for engines and components, both metallic and non-metallic, coupled with innovative low-cost manufacturing, will help drive engine and vehicle cost down if they can reduce weight and system complexity while increasing reliability.

Similarly, the cost of structures for expendable vehicles has been reduced because improved manufacturing processes have produced lighter-weight, high-efficiency structures. The Government in general and the Air Force in particular must play a central role in future ELV technology development efforts if it expects to continue to reduce the cost of getting to space. The AFRL plays an essential role in the development of new technologies that can be used by industry to reduce the cost of vehicles and improve their reliability. For instance, the Air Force Materials Directorate has a program that addresses materials for structures, engines, and sensors. This program, which also includes industrial partners, will result in the kinds of technology improvements necessary to further evolve ELVs into more efficient systems.

3.4 The Evolved Expendable Launch Vehicle Program

3.4.1 Description and Objectives

In 1993, DoD was directed by Congress to develop a plan that "establishes and clearly defines priorities, goals, and milestones regarding modernization of space launch capabilities for the Department of Defense or, if appropriate, for the government as a whole." Following a 1994 report on DoD launch system modernization options, the Air Force established the EELV program. The objectives of this program are to develop an expendable launch system evolved from current systems, or components, to satisfy medium and heavy space lift requirements.

The EELV mission statement says that the program will "partner with industry to develop a national launch capability that satisfies the Government's national mission model requirements and reduces the cost of space launch by at least 25%."[1] Furthermore, the program objectives are to "increase the U.S. space launch industry's competitiveness in the international space launch market and to implement acquisition reform initiatives resulting in reduced government resources necessary to manage system development and acquire launch services." This program just completed the pre–engineering and manufacturing development phase of a three-phase development program. The next phase is the award of two contracts (in September 1998) for development and initial launch services. The program plans to recover development costs in 2007, and it is anticipated that the EELV will save $5 billion to $10 billion through 2020.

The EELV program will develop three vehicles built around a "common core" but with different capabilities. The objective of these three vehicles is summarized in Table H-3.

Table H-3. *EELV Launch Capability*[2]

EELV	*Pounds to Orbit*
Small	4,800 GTO
Medium	10,000 GTO
Heavy	33,000 GTO

Because of the cost of Titan launches, EELV price reductions of 50 percent are more likely at the heavy-lift end of the spectrum. Medium- and high-lift prices are likely to decrease about 25 percent. These reductions in price per pound to orbit depend heavily on reduced processing time and increased production rates due to common cores and infrastructure.

EELV is an essential component of the Air Force's assured access to space for the next 20 years or until partially reusable or fully reusable vehicles demonstrate the reliability and cost-effectiveness necessary to replace them. The EELV program is not simply a new rocket program. It addresses all major aspects of cost reduction, including modernization of launch service, launch pads, vehicles, and operations. The EELV must be compatible with the existing range infrastructure and must plan for compatibility with future range upgrades. An important element of these upgrades is the ability to operate with the Global

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[1] EELV Mission Statement, http://www.laafb.af.mil/SMC/MV/eelvhome.htm, June 1998.

[2] SAF/AQS Presentation to Scientific Advisory Board at Spring Board Meeting, Falcon Air Force Base, April 1998.

Positioning System (GPS) as the EELV range safety tracking system. In Section 4.0, we discuss the importance of this requirement so that range operational cost can be reduced.

3.4.2 EELV Impact on Air Force Cost-Effectiveness

The EELV program requires heavy lift launch capability from both coasts. While this requirement is necessary to ensure that the Air Force can fulfill unanticipated requirements (no heavy lift launches from WR are scheduled through 2020), no business case has been advanced to access the cost of this "insurance." The Air Force should determine the real cost of this requirement to decide whether this cost is appropriate, given current funding needs.

A second issue related to cost-effectiveness is how to address launch-on-demand. In principle, a successful EELV program will result in a robust production environment. This will allow reduced prices and the possibility of carrying critical vehicles as contingency hardware, or so-called whitetails, to anticipate critical launch situations. Launch-on-demand, if handled incorrectly, may disrupt commercial customers and cause them to suffer financial loss. Disruption, or threat of disruption, of launch schedules will drive commercial launch customers to offshore suppliers. The net result will be increased launch costs for DoD customers, including the Air Force.

3.5 Recommendations

ELVs will be an essential component of Air Force assured access to space for the next 20 years or until partially reusable or fully reusable vehicles demonstrate the reliability and cost-effectiveness necessary to replace them. Until that time, the Air Force should support technologies that have a high payoff to reduce vehicle cost but increase reliability. Specifically,

- The Air Force should buy commercial launch services instead of buying vehicles. This means the Air Force must learn how to buy commercial and recognize where its requirements lead to increased cost, perhaps unnecessarily.
- The Air Force should continue to support its funding commitment to industry for EELV.
- The Air Force should seek to meet launch-on-demand needs by inventorying assets for quick buildup. The Air Force should avoid displacing commercial customers at ER and WR since disruption will drive customers offshore and increase Air Force launch costs.
- The Air Force should foster continued ELV technology developments through focused AFRL research (particularly in the areas of materials and propulsion) to reduce launch vehicle cost, reduce launch operational cost, and increase reliability.

4.0 Launch Infrastructure

The U.S. launch infrastructure is currently meeting the basic requirements to support both DoD and NASA. However, the infrastructure is expensive, is increasingly unreliable, and has very limited throughput. Without change it will be unable to meet the projected schedule of commercial launch requirements. The current upgrade plans will not resolve these issues.

The issues can be largely resolved by reducing the government-provided services, privatizing the necessary services, and evolving to a spaced-based range. This would permit the retirement of many high-maintenance assets and services.

4.1 Background

The current range infrastructure was created in the environment of developmental rocket testing. Testing of Redstone and Jupiter rockets progressed to the testing of intermediate-range ballistic missiles, such as Thor, and soon to testing of intercontinental ballistic missiles, such as Atlas, Titan, and Minuteman. Ballistic missile testing required precision tracking systems and telemetry receiving stations, both in the vicinity of the launch sites and downrange. The systems under test were all at the edge of the state of the art, and failures were common. Analysis of failures required both extensive on-board data and external radar and optical data.

With multiple development programs executing simultaneously, it was prudent to establish a common infrastructure to support testing and ensure safety of operations. An effective infrastructure was established for these purposes; it included downrange assets, command and control assets, and the ground base infrastructure for basic utilities, security, industrial security, and a host of other support functions. Since these capabilities did not exist commercially, the Government provided the entire infrastructure. For the most part, it is this range infrastructure that still exists.

Today, the environment is different for several reasons. There is very little development testing of rockets. Commercial launches now dominate, and this domination will increase in the future. Even government launches are dominated by operational launches, not test launches. The launches that are classified as test launches are usually not traditional rocket development launches. They may be launches of new reentry vehicles or new satellites, but the rocket itself is seldom under test. Follow-on test and evaluation launches of ballistic missiles are demonstrations, not development tests. Development launches of new commercial rockets usually involve only a flight or two rather than the many flights during the early history of modern rocketry. These limited development launches do not require the range infrastructure of the past.

Not only is the nature of the launches different, so is the technology. For instance, the tracking function can use GPS data instead of radar, and the range ground receiving station can be replaced by a station that acquires telemetry data relayed through satellites. These technologies would eliminate many, if not most, of the expensive and unreliable support equipment on the ranges.

In addition, the commercial industry has matured and can provide many of the launch and support services that the Government has traditionally provided.

This combination of changing missions and technologies along with increased opportunity to use commercial services suggests and enables major changes in the way the ranges do their business. To see this more clearly, we will present the functions of the ranges, problems in performing those functions, options to solve these problems, and some summary observations, conclusions, and recommendations.

4.2 Range Functions

Today ranges provide both primary functions and secondary support functions and capabilities. The primary range functions are the following:

- Protect people, property, and the environment through:
  - Flight termination
  - Flight safety analysis
  - Surveillance
  - Weather monitoring

- Provide operations planning and scheduling
- Perform data collection, processing, and distribution via:
  - Metric tracking
  - Telemetry
  - Optics
  - Data products

Although it is not listed as a function, the ranges support the military requirement for assured access to space. A related military requirement is launch-on-demand. The response time required for launch on demand is subject to different estimates, but all require disruption of launch operations. If a military launch must displace another launch, the disruption is obvious. If the military reserves a launch for possible use and that particular launch is not needed, it is usually too late to reschedule another launch in the vacated time frame. Thus, even this approach is disruptive to overall range throughput.

We questioned the appropriateness of Government—specifically Air Force—responsibility for each of the above in this new launch environment. For those items considered to be appropriate government responsibilities, we also questioned whether the Government should perform the functions associated with those responsibilities, or outsource the actual performance while maintaining an oversight role to ensure successful accomplishment. Our summary conclusions for the management of the primary range functions are as follows:

- Protect people, property, and the environment—the execution of this function can be outsourced, but we believe that the Government must maintain an oversight role. Oversight roles can vary from daily monitoring to periodic audits. We suggest that initial oversight be continuous with a plan to transition to periodic audits at a frequency sufficient to ensure continued compliance with requirements.
- Operations planning and scheduling—this function can be outsourced, with the Government maintaining oversight and the right to intervene. In particular, the Government must still ensure priority of military launches when necessary.
- Data collection, processing, and distribution—we question any government involvement in these functions. This is given the impact of an operations-dominated launch environment and the potential impact of modern technology that provides the opportunity for users to accomplish this function themselves.

Regarding assured access, we did not question the requirement, but did question the approaches to meeting the requirement. These approaches will be discussed later in Section 4.3.5.

The secondary, or support, functions provided by today's ranges include the following:

- Utilities, to include power, water, sewer, and communications
- Industrial safety (contrasted with range safety and addresses the safety of the pad and support processes)
- Physical security
- Support equipment and services, to include trucks, lift vehicles, "cherry pickers," and photography

- Military housing

We believe that all secondary services can and should be provided commercially. The commercial launch provider can and should be completely responsible for all activities within the pad perimeter, to include adherence to state and Federal industrial safety regulations. This would enable each user to tailor the services to specific needs.

4.3 Range Concerns

Several issues have arisen because the fundamental nature of the range infrastructure is mismatched with the evolved mission of the ranges. These include inadequate range throughput to handle the demands of the future range users, a decreasing reliability of range operations, and increased costs.

These issues create undesirable consequences for the modern users. Neither commercial customers nor government range users can depend on executing their launches when they need to. In the commercial world, financial impacts can be very substantial and can motivate commercial users to seek alternative launch sites, including foreign launch sites. This has serious consequences for the United States' economic, technical leadership and, as demonstrated by recent events, may have security implications. Finally, there is a financial impact that is spread in various ways among the Air Force, government agencies, and commercial users.

These generic issues create a number of specific problems, described in the following subsections.

4.3.1 Throughput

The demand for launches will increase in the near future due to the trend that commercial launches are increasing faster than the fall-off in government launches. The supportable launch rate is anticipated to fall below the demand in 5 years or less. While there are uncertainties regarding the future demand for launches, there is no doubt that the demand for range services will exceed capacity within the next several years.

Throughput has multiple dimensions: launches per unit time, time required to switch from one launch operation to another, the ability to support multiple operations simultaneously, and the reliability of the launch support operations. Each of these specific dimensions has problems.

Current throughput of the ER is limited to about 43 launches per year. By 2001, the demand for the ER is expected to reach about 50 launches per year. On the other hand, demand for the WR is expected to remain well below the capability of 25 per year through 2010. Current upgrade plans could close the ER gap by about 2006, but the effort is subject to both uncertainties in funding and the timing of the growing demand.

Today, ranges have limited or no ability to support multiple concurrent operations. This means that a second operation can't start until one is complete or aborted. Even with the trend toward quicker launch processing, this limitation places a severe constraint on overall range throughput.

The throughput and range turnaround problems are due to both architectural and operational factors. For example, the current system at the ER uses an outdated video switch patch panel. Consequently it takes up to 8 hours to reconfigure the communication, between operations, another 8 to 12 hours to do configuration tests on the instrumentation systems, and another 8 hours or so for final configuration checks.

For operational considerations, the crews must rest overnight between the initial checks and the launch operation. Thus the range can easily use 3 days to a week between launches, even more with equipment failures. This severely limits the flexibility to adjust the launch schedule to accommodate another system launch if the first is having problems.

4.3.2 Decreasing Mission Reliability

Mission reliability is influenced by the range's ability to perform its functions so as to permit a launch to occur on schedule and its ability to execute the range safety function reliably after launch.

An example of how hard it is to support an on-time launch is the difficulty in maintaining satisfactory radar coverage for the duration of the prelaunch processes. Several countdowns have been put on hold and launches have been canceled due to problems keeping the range support systems operating. To improve this, the ranges enable more radars than normally required with the hope that redundancy will make up for the lack of reliability. Despite this, the lack of range reliability continues to be a major problem. The Cassini launch on a Titan IV involved 23 range system events in which the range went "red" during the count. This gives us the impression that the range is barely hanging on during a number of these launches.

An even more severe reliability problem is the flight termination of good missions. This has happened at least once at each range during the past 5 years. The unreliability of safety-related range equipment translates directly into higher probabilities of terminating good flights because the priority of safety is higher than the priority of the mission. However, this should not be a justification for upgrading old range-safety systems. It appears appropriate to change the nature of the systems from ground-based radar systems to GPS-aided approaches—which can both increase reliability and reduce cost.

4.3.3 Increased Costs

The total cost of range usage comes in two forms. One is the cost of range operations; the second is the induced cost to the launch and payload contractors who must conform to extensive range requirements in their designs as well as their operations. The first runs over $500 million annually, not including upgrade costs, and is spread by various methods over the Air Force (as the range operator) and over users. The second is difficult to estimate accurately, but is considered significant by the users who shoulder them directly.

There are discussions about shifting more of the "standing" costs of the range to the users (who currently pay only the incremental costs associated with their specific operations). There are important policy considerations in this regard, and we considered those to be outside the purview of the Air Force Scientific Advisory Board (SAB) study. Instead, we focused on how to reduce the costs, not how to spread them.

A cursory examination of the O&M costs shows that most of the costs are for other than primary range functions, namely, the cost of the base infrastructure and the government "way of doing business" by using the procedures, processes, and equipment of the early 1960s. These costs include housing, security, roads and grounds, facility maintenance, and numerous support services that are the necessary costs in maintaining a military base. Almost all of these costs could be drastically reduced or eliminated with change.

The costs are consumed by a large assortment of contracted and government-provided services and support activities. These are semi-fixed overhead costs and do not vary with launch schedule. This is in addition to the launch and payload teams that are funded by the individual government and civilian launch service teams and payload programs. There are, for example, about 9,900 military, civil service, and government contractor personnel employed by the ER and WR. The total number of range-funded personnel has been reduced in recent years (by 667 in 1997 alone), but appears to have room for much greater reduction.

We believe that a large portion of these costs could be reduced or eliminated, but it will take a major change in what is provided and the way it is provided.

4.3.4 Inability to Attract Users

Although few users will state directly that they have moved to other ranges because of problems with the existing ranges, a number *have* moved, and they have noted the attendant advantages. Both X-33 and Sea Launch will launch from alternative sites. Both can cite performance and operational advantages, as well as other benefits, for their choice. Kistler Aerospace is planning its initial launches from Australia because launch capability can be ready in less time there than at a U.S. range. Collectively, these examples suggest a trend toward reduced satisfaction with existing ranges.

In some cases, the demand of satellite manufacturers for numerous launches, particularly launches associated with the new LEO constellations, have forced the manufacturers to seek launches from almost every available source, domestic and foreign. It is hard to predict accurately the level of such launch activity after these constellations have been initially populated, but maintenance and replenishment of the constellations will certainly cause launch activity to be higher than before the LEO deployments.

This phenomenon is compounded by the advent of other ranges competing for the business of the national ranges. The proposed range at Kodiak, Alaska, is directly targeting operations currently launched from Vandenberg AFB, California. Foreign competition exists for ranges as well as launch vehicles.

Given the problems with meeting future demand, some might say a migration to other ranges is helpful. There are major implications of any such migration, particularly to offshore locations. We assumed that we should not depend on such a migration to solve the throughput problem, but should work on solving the throughput problem to avoid necessitating a migration. Also, it is clear that migration will not resolve the issue of inadequate capacity to handle the demand at the ER. This is because EELV contractors are establishing their launch sites at this range, and this traffic alone will cause the demand to exceed the range capacity.

The movement to alternative launch sites also provides an opportunity for case studies of the necessity for many of the standard launch services. For example, the panel was impressed with the “bare bones” approach and low projected cost for the planned Kistler launch operations in Australia, and with the reduced cost for the launch support system for the NASA/Lockheed Martin X-33 test vehicle.

4.3.5 Assured Access to Space

The Air Force requirement for assured access to space was not studied in detail. We did not, for example, examine options for the loss of a range. However, we can make the following observations:

- First, the loss of a range is likely to be due to either reliability problems or terrorists. Reliability should be greatly improved with the current upgrade plans, but an even greater improvement would come from the replacement of radar with GPS and from the elimination of data retrieval and processing by the Government.

- The vulnerability to terrorists would be greatly reduced by eliminating the downrange assets, which are inherently difficult to protect.

4.4 Solution Options

These problems have not gone unnoticed, and multiple efforts have been directed at fixing some aspects of these problems. Some efforts are in the implementation phase, while others are still studies.

4.4.1 Current Upgrade Programs and Studies

4.4.1.1 Range Standardization and Automation Program

The Range Standardization and Automation (RSA) program was started in 1993 to improve reliability and throughput of operations, standardize the WR and ER, and reduce life-cycle cost. The total investment is estimated at $715 million. Delays in funding portions of this project have moved the completion date to 2007. Projected life-cycle cost savings is $2.1 billion, but it appears that the first dollar of savings will not show up on the books until about 2004 or 2005. There will be savings earlier because of increased range reliability and the ability to handle greater throughput, but these cannot be easily quantified.

A problem with this program is that it is basically upgrading the equipment to do business the old way; it does not reengineer range operations to reflect the new environment mentioned at the beginning of this section. Upgrades to precision tracking radars are planned but are not needed with GPS-based systems. Upgrades to telemetry support systems are planned, but modern users don’t need them, especially the downrange receivers. It appears that this program should be reprioritized against a set of metrics to include throughput, reliability, and operational costs. Also, the reprioritization should consider upgrades to new ways of doing business; more will be said about this later.

A further problem is the instability of funding. Funding cuts in various years have already moved the completion date out several years, and there is no reason to believe the remaining funds will not also receive cuts. This problem suggests the pursuit of alternative methods of funding upgrades.

4.4.1.2 Improvement and Modernization Program

The Improvement and Modernization (I&M) Program is directed at continuing sustainment of existing range systems, particularly those that are not part of the RSA program. The I&M Program is significantly smaller than the RSA program, but does include modifications to upgrade fielded equipment.

4.4.1.3 General Henry Study

A study of range operations and ways to improve them, under the leadership of Lt General Richard Henry (U.S. Air Force, retired), was commissioned by General Estes, was conducted in parallel with the SAB Summer Study, and involves several panels of knowledgeable Air Force team members. It is tasked to address the following:

- Scope the capability of the DoD ranges to support a robust space launch capability over the next 10 years
- Define opportunities to increase space launch potential
- Recommend policies for customer use of limited resources
- Identify opportunities for improved support to commercial users

The report is scheduled to be completed in September 1998. We talked with General Henry during the course of our studies and believe that both studies are reaching similar and noncontradictory conclusions.

4.4.2 New Spaceports

New spaceports are in various stages of development. California and Florida are developing spaceports. Both provide the Air Force with options for some of the range and launch base support infrastructure on the existing ranges. The two spaceport initiatives have slightly different approaches and different degrees of maturity. The Florida Spaceport Authority has assumed a role similar to an airport authority's and is sanctioned under state law. It plans to provide infrastructure development and modernization, infrastructure brokering to provide access to multiple users, and financing for infrastructure projects through bonds, grants, loans, and lease-back arrangements.

The California Spaceport initiative is a private venture. It has secured 110 acres of unimproved land on South Vandenberg AFB and plans to build a launch site. It also plans to broker and/or provide a variety of launch support services. It has already provided some satellite processing support.

Several states are planning new spaceports. The Alaska Spaceport is scheduled to have its first launch during the fall of 1998. Sea Launch will be operational early in 1999, if not before. If these spaceports succeed at reducing costs and improving launch reliability, they may draw some of the planned launches from the ER and WR and, as such, may reduce the throughput problem. However, until these spaceports become truly operational, it will be unclear whether they really will achieve the desired launch reliability and the desired reductions in launch costs. In any case, they will not fix the launch reliability and cost problems at the ER and WR.

4.4.3 New Technologies and Methods of Operation

The advent of new technologies, such as GPS navigation, and new capabilities, such as relay of data through NASA's Tracking and Data Relay System (TDRS), enable new methods of operation that promise improvements in several key metrics: launch reliability, range throughput, and cost.

The use of GPS to provide data for range safety is already in limited use for the Navy Fleet Ballistic Missile testing. The concept can be extended to cover all new launch vehicles, and with an appropriate phase-in of this capability, the radar tracking systems can be phased out of operation. This will have a major impact on cost and launch reliability. Some current users will find reasons not to make the conversion, but we suggest that a limit be put on the time during which radar tracking will be provided. Users who have not converted to an alternative system by the end of this time can elect to take over the operation and maintenance of the radars for their own use. The Government should not allow itself to be trapped into being the permanent owner-operator of an expensive resource that is not needed.

Air Force Space Command has a draft plan (now in coordination with the user community) to transition the ER and WR to GPS metric tracking by FY 04. This would enable the ranges to retire 12 radars used solely for launch vehicle tracking (6 radars on each range). The panel endorses the intent, but feels that the plan can and should be accelerated. We also believe that with the satisfactory test of the GPS metric tracking, the Air Force should consider retiring or transferring all multiuse radars to another account. This would ensure that the O&M costs of the radars are justified or retired by the remaining user(s), and not carried on the launch range O&M account.

Downrange telemetry stations can also be phased out. Some users, such as Atlas, already relay their data through TDRS; with time, all users can find alternatives. The only telemetry receivers that may need to be continued are some in the immediate launch area, and even this requirement should be challenged. Phaseout of the downrange telemetry stations will have a significant impact on cost and on system vulnerability to terrorists.

These two examples set the stage for a recommendation that the ranges be reengineered to be space-based ranges, which we define as phasing out of ground-based tracking and telemetry systems in favor of satellite-based data relays and GPS-based tracking systems. At the very least, such an approach should eliminate all downrange assets. The satellites for data relay should not be provided by the ranges, but should be ones already available, such as TDRS. Many in the range community already support these ideas, but some will resist such a transition. Resistance will come both from users and from personnel within the range infrastructure who have interests in the current ways of doing business. Strong leadership is required to make a change like this happen, and we suggest that a fundamental change in the overall management of the ranges would greatly facilitate this change.

4.4.4 Range Privatization

We believe that range privatization should be considered for two reasons. First, it is an approach to achieve real savings that could be used to solve the reliability and throughput problems. Second, it provides a means to effect change in the standard way of doing business, which should in turn provide additional savings and improved throughput.

The combination of shortfalls of funding for operations and possible resistance to change from some within the community suggests that a fundamental new approach to range operations is in order. In particular, we suggest that the ranges be changed from government operations to contractor operation with government oversight.

A promising model for the contractor operation is the United Space Alliance, which performs Shuttle operations. In this model, the contractor is committed to savings as a result of efficiencies the contractor could implement. A portion of these savings can then form the basis for a funding wedge from which to fund future modernization. This would greatly reduce the sensitivity of the range performance to government funding cuts.

The government oversight should be tailored for each function of the range. The oversight of the safety function can be modeled after Federal Aviation Administration (FAA) oversight of commercial aircraft operations. The oversight of the operations and planning function should be limited to that necessary to ensure that the Government could maintain assured access to space and, when a situation demands it, that the launch-on-demand requirement can be met. There should be no oversight of the data function because we believe that the ranges shouldn’t be in this business in the changed environment in which operations become dominant over testing.

Contractor operations can take any of several forms. One possibility is to privatize the operations as they exist today. Another possibility is like an airport: the overall operator provides a number of the generic functions, but users get their own “terminal buildings” within which they are responsible for their individual and peculiar operations. Whether it is a terminal building or a fenced-in launch area, the principles are the same. There are other models, and it is not our intent to do a trade study on which model is most appropriate. Suffice it to say that models exist that provide significant improvement in operations and costs. These models also improve the ability to handle internal resistance to change.

Privatization also has the advantage of reducing the political sensitivity of reducing staffing levels at the ranges. There is less political concern about reduction of contractor personnel than government personnel.

There are several limited privatization activities in plan or actually in work within the range infrastructure, and they have met with some success. We believe that to meet the full potential of cost savings, the concept should be extended to all services in a “zero-based” budgeting approach. This would include the primary range functions as discussed above, as well as the launch base ground support functions and the host of infrastructure items. For example, it should also include such services as roads and grounds, industrial security, firefighting, weather forecasting, and facility maintenance.

4.5 General Observations

Although the majority of our time was spent studying specific issues, the process led to these noteworthy generic observations:

- The vast majority of launches are operational, carrying either commercial or military payloads, and most of the remaining launches are either continuing demonstrations of missile capabilities or tests of rocket payloads rather than rockets themselves.
- The few remaining true test launches of rockets do not require the range infrastructure of the past.
- There is a limited recognition of the above observations, and this had led to the continuation of programs that do not prepare the ranges for their modern roles.
- While many people in the various commands recognize and desire the needed changes, there is not a strong forcing function to make these changes happen. Everyone seems to be asking for permission rather than taking charge.

4.6 Conclusions

- The test missions that the ranges were designed to support have been largely supplanted by new operational and commercial missions.
- The ranges cannot support the projected increase in commercial activity.
- The current plans will not correct the problems of O&M cost, reliability, and throughput and will lead to serious undersupport of our nation’s launch requirements within the next few years.
- Current and available technology can greatly improve the O&M cost and throughput of the ranges.
- Significant changes must take place in both the technical approach and the management approach to the ranges.

4.7 Recommendations

The recommendations of the panel are as follows:

- Reprioritize the currently planned RSA and I&M upgrades against specific metrics of annual maintenance costs, turnaround time, and mission reliability.
- Redefine the range functions to reflect the strong dominance of operational launches and the diminishing mission of rocket testing. Specifically,
  - The ranges should provide the minimum essential services for safety and operations planning and for those common services that can be justified on cost. For example, the ranges should plan to get out of the data retrieval and reduction business. Today, most users prefer to reduce their own data.
  - Both the safety and operations planning functions should reflect operational launches first and require testing to fit into the resulting infrastructure, rather than the other way around.
  - The ranges should also get out of the launch base infrastructure business.

- Reengineer the ranges to be space-based.
  - Close down all downrange tracking and telemetry assets.
  - Change to GPS-based tracking for range safety, and shut down all radars.
- Initiate efforts to turn range operations and launch base infrastructure support over to a private contractor in the form of an omnibus contract, with the following constraints:
  - The contractor to generate funds for range maintenance and upgrades from the savings achieved through efficiencies introduced by the contractor.
  - The Government to retain oversight roles for the safety function similar to that provided by the FAA for commercial airlines.
  - The Government to retain the right to modify operations planning as required to maintain the military's assured access to space and, when required, launch on demand.
  - The contractor to be allowed to replan the RSA efforts as required to achieve the efficiencies and improvements against the metrics.
  - The launch service users to decide what launch base infrastructure support they obtain from the private contractor.
- Plan to transfer launch infrastructure responsibility—safety to an appropriate agency, operations to a National Space Port Authority. This may require up-front investment to realize savings.

5.0 Reusable Space Launch Vehicles

5.1 The Case for Reusable Launch Vehicles

The Aerospace Force of the future clearly must rely on affordable and timely insertion of vehicles into space. While ELVs are the mainstay of access to space for the Air Force, there is a need to further reduce the cost of launch. Launch price to GTO for current ELVs is shown in Figure H-1.[3] Trend lines for Ariane, as well as those anticipated for China and Russia, are shown for reference. (The true price for foreign launch is very difficult to determine due to foreign government subsidy.)

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[3] U.S. Air Force Scientific Advisory Board Study, *Space Launch*, SAB-TR-9405, March 1995, Figure 16.

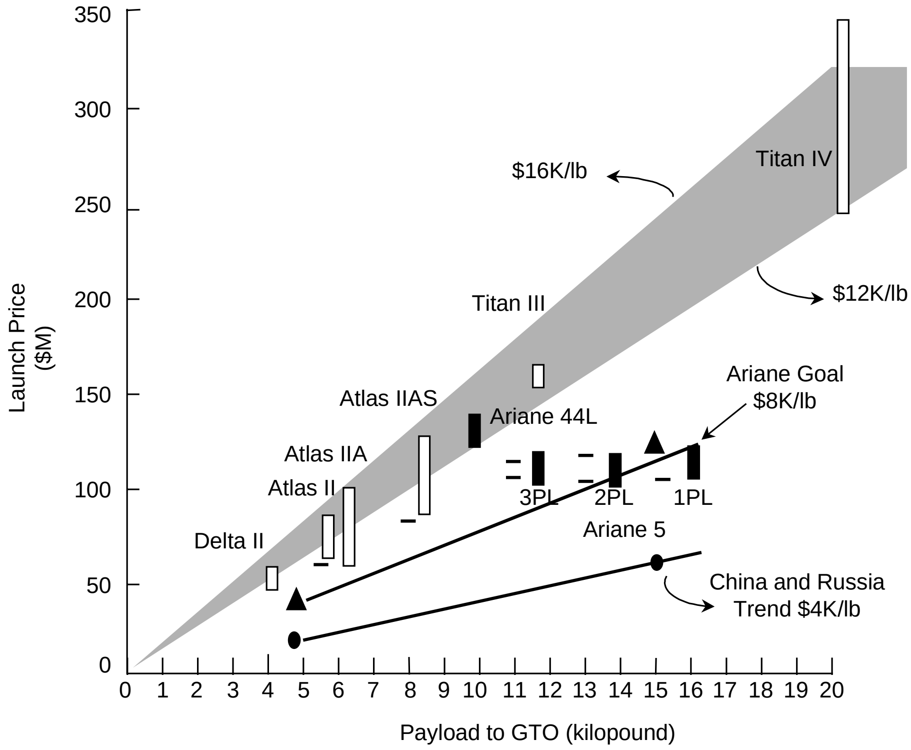

Figure H-1. *Launch Price to GTO for Current Expendable Launch Vehicles*

The expected launch price for EELV is on the order of $2,000 per pound to LEO and $6,000 per pound to GTO. There does exist a finite limit to cost reduction for ELVs since all launch hardware is expended for each launch.

RLVs offer the potential to reduce launch costs significantly below ELV levels, perhaps to hundreds of dollars per pound to LEO rather than thousands. However, to reach this full potential, RLVs must trade high development costs against reduced operations cost. The initial cost of development is high, and there is significant technical risk in the development of RLVs. To reach the potential dollars-per-pound launch savings, the business case requires a high launch rate with airplane-like reusability over an extended period.

RLV is clearly the way for the future and promises the lowest cost for satisfying Air Force launch requirements. The only issue is when the technology and demand for commercial, national, and military launch will provide the proper environment. If RLV operations can provide rapid turnaround, as is the case for air freight, the Air Force should benefit with launch-on-demand potential.

5.2 Entrepreneurial Approaches to Reusable Launch Vehicles

Several entrepreneurial companies are undertaking RLV approaches. Two of these are Kelly Space and Technology and Kistler Aerospace Corporation. The concepts are restricted to light to intermediate launch payloads and are being pursued under private funding. The Kelly vehicle is a tow-to-launch concept. The Kistler concept is a 2½-stage recoverable rocket booster.

The Kistler RLV approach appears to be the more mature of the two approaches. Kistler anticipates a capability to launch payloads of approximately 10,000 pounds into LEO at a launch cost of roughly $17 million per launch, or $1,700 per pound. Current plans call for first flight in 1999. The concept offers an attractive and relatively low-risk approach to recoverable launch for medium payloads, but may not scale up to heavy payloads. Even though the approach is sound from the perspective of technology maturity, it faces development and market risk in a challenging business environment.

If successful, these privately funded RLV approaches could offer the Air Force a future alternative for medium to intermediate payloads.

5.3 NASA Approach for Reusable Launch Vehicles

The National Space Policy of 1996 gives NASA responsibility for technical development of RLVs and the Air Force responsibility for ELVs. In response, and as a potential replacement for the Space Shuttle, NASA has initiated the X-33/Venture Star program. The program is designed to provide the technology base and to provide flight demonstration with a suborbital X-33 vehicle. Further development of a full-scale RLV depends on industry investment.

5.3.1 Single Stage to Orbit

The NASA/Lockheed Martin team has selected a SSTO approach for the RLV. The X-33 half-scale suborbital flight demonstrator will provide the technology maturation required for development of the full-scale RLV. Its introduction into the launch market dependents on two factors. One is satisfactory reduction of technical risk through the X-33 demonstrator. The second is the existence of a strong business case to justify industry investment in the development of the full-scale vehicle.

The single NASA program contains significant technical risk. The X-33 technology demonstration plan is shown in Figure H-2. Even if the X-33 suborbital demonstrator is successful in the maturing hypersonic technologies, risk still remains in scaling from the X-33 to the RLV and in obtaining design and business plan closure for a full-scale RLV. The current program plan, shown in Figure H-2, is aggressive, calling for a full-scale development decision in 2000. It might be reasonable to expect that the decision point and RLV availability will slip to the right.

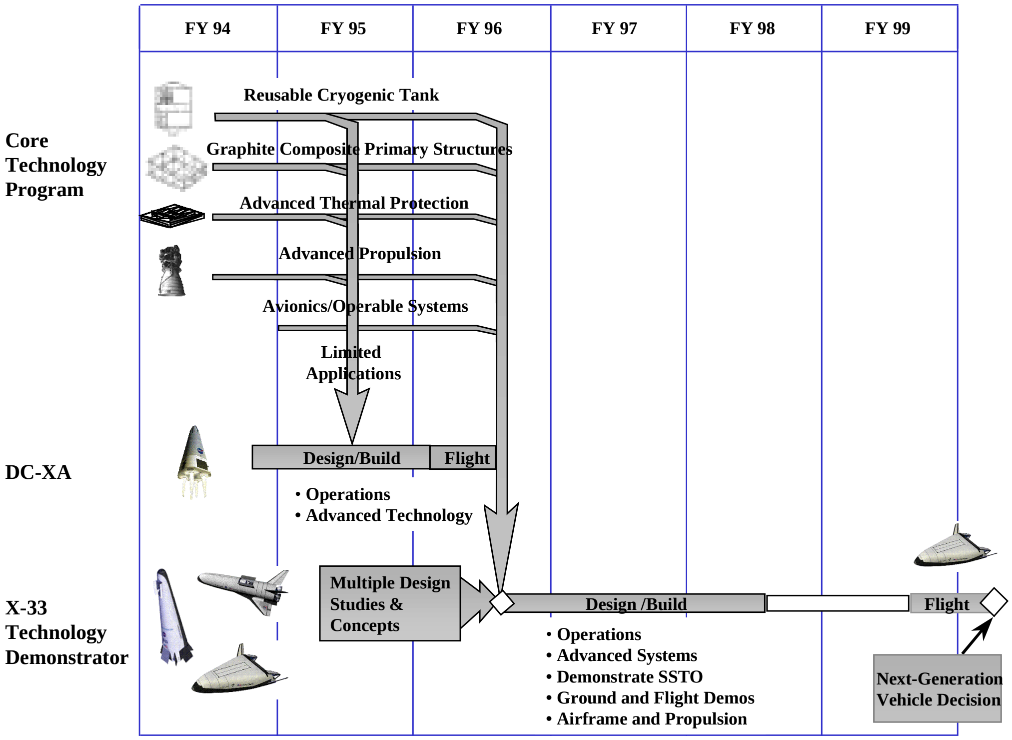

Figure H-2. *X-33 Technology Demonstration Plan*[4]

The full-scale SSTO launch vehicle relies heavily on industry investment. The nonrecurring costs and development costs are high for this class of vehicle. From a business standpoint, amortization of these costs is key to making a decision to go ahead. The business case then for RLV will depend on a stable, long-term market need for 30 to 50 launches per year as well as a vehicle that has low operations cost and rapid turnaround capability. Thus, the business case may depend on some government commitment—for example, space station launches by NASA or other market commitments for launches by other government agencies, including the Air Force.

5.3.2 Two Stage to Orbit

A TSTO vehicle system contains lower technical risk. However, the SSTO vehicle offers superior operational benefits. Table H-4 compares the advantages and disadvantages of the two from an operational standpoint. If for any reason the development of the SSTO fails to materialize, a TSTO concept may hold promise for further evaluation.

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[4] Gene Austin, NASA Marshall Spaceflight Center, “X-33 Program Overview to the U.S. Air Force Scientific Advisory Board,” Presentation to Scientific Advisory Board Vehicles and Lift Panel, Alexandria, VA, 15 April 1998.

Table H-4. *Reusable Single-Stage-to-Orbit Launch Vehicle Compared to Two-Stage-to-Orbit Vehicles*

SSTO	*Comparison*	*Comments*
Advantages	• Lowest operating costs	Fewer people for turnaround
	• Fewer operations restrictions	No stages dropped, no boosters to recover, simple basing and site
	• Simpler launch operations	Simpler fueling, no stages to mate or integrate
	• Higher reliability	Lower parts count, fully understood vehicle
Disadvantages	• Larger development cost	Requires a higher flight rate to amortize investment
	• More demanding in performance	More demanding structure, tank, and engine technologies
	• More payload sensitivity	More sensitive to weight growth during development and increases to on-orbit delivery altitude and inclination

5.3.3 Risk Reduction

Failure of the NASA program to reach a successful RLV for either technical or business reasons could be catastrophic for the near term. Government investment in a heavy-lift RLV new start would be unlikely for a decade or more, at least.

A funding shortfall in the NASA program has been identified in the 1999–2001 time frame for dealing with some risk-reducing technologies. At this point in the RLV program, small investments in science and technology (S&T) could have huge payoff in reducing the risk for a full-scale launch vehicle. The Air Force could offer help by focusing some of its S&T program money to support some of those technologies that are equally important to the operational space vehicle concepts being pursued by the Air Force. Health monitoring of temperature and pressure at extreme conditions, propulsion technologies (such as alternative fuels, or enhanced performance combustors and ejectors), some long-life testing of engine systems, and large-scale integrated thermal structures are important technologies not adequately being addressed.

5.4 Conclusions

- RLVs offer the best hope to reduce significantly the cost of launch for the Air Force.
- Private enterprise development of reusable launch capability for intermediate to medium payloads may offer some opportunity for the Air Force in the future.
- Intermediate, medium, and heavy-lift launches are the goal of NASA’s X-33/Venture Star program.
- It is in the Air Force’s best interest to help at the S&T level with risk-reduction technologies that also are important for an AOV system.

5.5 Recommendation

Coordinate with NASA on the X-33/Venture Star RLV program to identify opportunities consistent with the AOV system needs and take responsibility for near-term support within the existing AFRL resources.

6.0 Aerospace Operations Vehicle System

As the Aerospace Force enters the 21st century, more and more of the assets necessary for national defense will reside in space. Furthermore, as the 21st century unfolds, more and more of the commercial interests vital to the economy of the United States will reside in space. Thus, for the U.S. Space Command to fulfill its mission as enabler of military operations and to protect the vital national interests, a new requirement emerges: to protect the vital space interests and to integrate the military structure with space. This leads to the need for a highly responsive reusable space operations vehicle that can be used for multiple missions within and outside the atmosphere. The AOV has been proposed to specify the vehicle, or system of vehicles, needed to accomplish multiple space missions.

6.1 Missions and Requirements

The Air Force Space Command has developed a Mission Needs Statement and a CONOPS for a vehicle called a space operations vehicle. This vehicle, or system of vehicles, is intended to supply the Air Force with a force-multiplier capability that strengthens the national defense with rapid placement of lethal and nonlethal space control, on-demand constellation replenishment, and on-orbit satellite retrieval or recovery. The CONOPS for the space operations vehicle has defined the following utilities to be performed:[5]

- Counterspace operations
- Real-time protection of domestic and friendly force on-orbit assets
- Rapid recoverable intelligence, surveillance, and reconnaissance (ISR)
- Satellite deployment, redeployment, recovery, upgrade, refueling, and repair
- Space-based deterrents in areas unreachable by land, sea, and air forces
- Space-based resource integration into the conventional force package
- Worldwide weapons delivery within minutes of launch

AFRL, in conjunction with its contractors and Air Force Space Command, has worked at an S&T level to define possible approaches for such a system. These studies have concentrated on a two-stage system in which the second stage is an SMV. The first stage is generally thought of as a new vehicle that may have hypersonic capability, or it could be NASA’s RLV or a derivative of that concept. Other options are possible for the first stage, depending on the required robustness.

The operations concept described above forms a basis for the AOV system reported here. The next section will weigh some of the options and provide a recommendation for near-term action.

6.2 AOV System Approaches

6.2.1 Single Stage to Orbit

There are several approaches apparent for an AOV system; two stand out as significant. One is an SSTO concept that might be based on the NASA X-33/RLV program; the second is a TSTO concept in which there are numerous options for the first stage. From an operational standpoint, the most pleasing

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[5] Concept of Operations for the Phase I Space Operations Vehicle System—HQ AFSPC/DOMN, 6 February 1998.

approach is to have a single-stage vehicle that flies from runway to orbit, accomplishes maneuvers in orbit as required, reenters, and lands horizontally. Ideally, this concept would be able to cruise in the atmosphere hypersonically to accomplish suborbital missions including strike or ISR, for example. This concept would have the most airplane-like operational scenario, which is understood extremely well by the Air Force.

The advantages and disadvantages relative to a TSTO concept are the same as those given in Section 5.3. The NASA RLV program can provide important technology maturation steps and validation of systems concepts that would apply to an Air Force SSTO AOV system. However, the commercial RLV could not be considered as an AOV candidate for the Air Force because the commercial RLV lacks both the basing flexibility and the rapid turnaround capability desired for a military space plane.

The development costs for an SSTO AOV system would be very high even if the NASA/RLV maturation program is successful. The expected high development costs, along with the very high-risk nature of the development, would seem to preclude the SSTO RLV as a viable candidate in times of austerity for the Air Force. If ongoing NASA technology maturation programs are successful, and if the market-driven RLV evolves, a strong case for an SSTO AOV system can be made for the future. At some point SSTO may then become the preferred vehicle configuration choice.

6.2.2 Two-Stage-to-Orbit

A TSTO AOV concept offers a much more affordable approach and much lower risk for the Air Force. The second stage in this concept can be a relatively small, straightforward SMV carrying appropriate light payloads and with enough delta-V to go into orbit and perform maneuvers and operations in space before returning to earth and landing. The SMV can be a suborbital deliverer for sensors or a weapons carrier that can reach any point on earth in a very short period of time and be recovered in a conventional landing.

Many options are possible for the launch vehicle. These range from a new hypersonic (say, Mach 15) airplane-like first stage to an air launch from a large aircraft or launch from an existing ELV. The new hypersonic vehicle for first stage would offer maximum utility and robustness with perhaps minimum response time. This vehicle would be more costly than other options as far as development is concerned, and has higher development risk. However, it could draw on X-33 technology being developed as well as take advantage of the NASA technology development in future hypersonic programs such as Hyper-X. The TSTO approach has inherently lower risk than SSTO and has the distinct advantage that it can be developed incrementally—that is, one stage at a time. This feature is attractive from a budget standpoint.

The SMV second stage is a workhorse that performs a wide variety of utility tasks in and out of orbit and returns to land. The SMV, as envisioned by AFRL, can be a low-risk vehicle that is doable today with known technologies. The first stage, or launch vehicle, for the SMV can be an airplane drop or an ELV, maybe a Minuteman. An SMV launched from available assets can perform a large percentage of the utility tasks envisioned for an AOV system. The exceptions are, perhaps, rapid reaction capability and the robustness that could be supplied by a new first stage with flexible basing capability.

6.3 Space Maneuvering Vehicle Demonstrator

An SMV demonstrator vehicle could be developed and flown in the near term as indicated by the AFRL studies. These studies show that a reusable SMV demonstrator weighing on the order of 10,000 to 12,000 pounds could be launched by an ELV, airplane, or Shuttle and carry a payload of 1,200 to 2,500 pounds. This vehicle could be flown within a reasonable time frame (3 to 4 years) at a cost that would not break the bank. Approximately $35 million per year for 4 years would be required.

The AFRL has sponsored a significant amount of preliminary work in conjunction with contractors. The technology is in hand and technical risk is expected to be small. The demonstrator would be used not only to validate the technical feasibility, but also to verify the usefulness of such a vehicle to perform the utility operations required in the Air Force CONOPS. The vehicle could demonstrate the ability to rendezvous with satellites on orbit, to position the SMV to simulate maintenance functions or for refueling of satellites in orbit, to simulate satellite retrieval, to simulate space control options, or to simulate global positioning for ISR or for weapons delivery. The demonstrator could be used to give confidence in the utility of an SMV as well as to verify the CONOPS while learning how best to use its capability.

6.4 AOV Program Plan

A suggested development roadmap for an AOV system is given in Figure H-3. The NASA X-33/RLV program is shown for reference only. The AOV program plan is constructed for a TSTO system. The higher-cost first-stage development is moved downstream primarily to comply with known budget constraints but also to allow for key technology development. As the NASA RLV program progresses and as the AFRL continues its S&T efforts, technology maturation is expected to feed into the first-stage development.

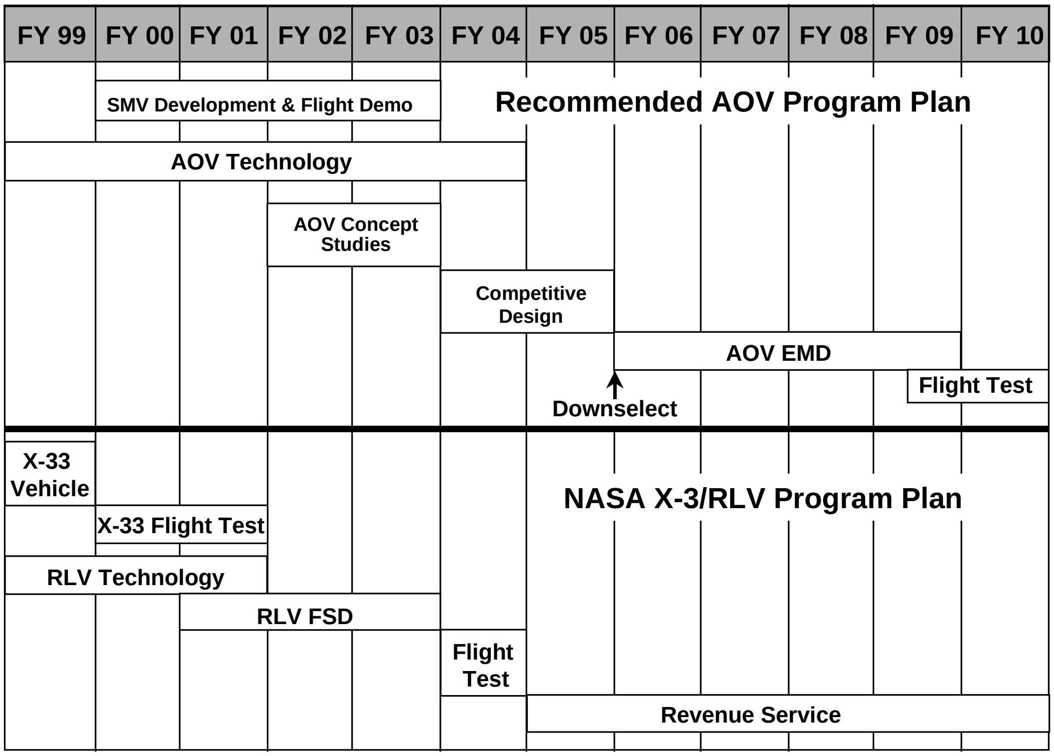

Figure H-3. *AOV Development Roadmap*

Critical to the plan is a continuing technologies program that specifically supports the AOV. This technology is pursued by the AFRL and should be tied closely to the NASA RLV technology work, as was explained in Section 5.3.3, and the Future-X series of demonstration programs planned by NASA. This technology effort can be funded within the AFRL budget line and could be enhanced by shifting emphasis from some of the less important technology areas.

The linchpin for the recommended program is an SMV development and flight demonstration program. As discussed in the previous section, the SMV is the heart and soul of the desired capability for the Air Force. This work leading to a flight demonstration should begin as soon as possible and be pursued with intensity to verify the concept and the utility of the second-stage vehicle.

The plan has allowed for the concept development for a first-stage vehicle to begin well into the SMV flight demo program and could be slipped even further to the right depending on budget requirements and a validated need for a new first-stage vehicle. It is conceivable that existing launch options will provide the capability the Air Force needs in a satisfactory manner (say, 85 percent capability) and that the price to be paid for a new first-stage vehicle is not warranted. The schedule and drivers for a new first-stage vehicle must be based on national need and budget priorities.

As discussed in Section 6.1, the NASA X-33/RLV program is important for a national launch capability at low cost. Its technical constraints are large, and the program could well be expected to slip to the right as far as developing an RLV is concerned. The following two points are important:

- The Air Force AOV program does not depend on the success of the NASA program unless an SSTO AOV system is envisioned for the future.
- The RLV that results from the NASA program is not satisfactory for the envisioned fast-reaction AOV system because it will not provide the desired launch-on-demand and basing flexibility. However, the NASA program can supply technology and confidence for the future.

6.5 Conclusions

- An AOV system can give the Air Force unique capability to perform global strike/ISR, space control, constellation replenishment, and on-orbit retrieval or servicing missions.
- A phased development plan can evolve the AOV system capability in a fiscally responsible manner while providing the opportunity to prove the utility of the concept and verify the Air Force CONOPS.

6.6 Recommendations

- Proceed with an SMV demonstrator program as soon as possible to verify operational concepts and gain confidence in the new capability.
- Develop a follow-on AOV plan and roadmap for an appropriate first-stage vehicle.

7.0 Spacecraft Buses

7.1 Overview

7.1.1 Commercial Satellite Trends

Significant trends are developing in the commercial satellite industry. The most obvious is the explosive growth in terms of both revenue and units delivered. Other trends are perhaps less obvious. The Air Force can significantly reduce cost and cycle times by leveraging the commercial industry.

Commercial satellite growth is driven primarily by global deregulation and privatization of the telecommunications industry. According to the Teal Group, over the next 10 years 1,697 satellites worth approximately $120 billion will be procured. The breakdown by sector is as follows:

Defense	23.6%
Civil	25.3%
Commercial imaging	3.2%
Commercial communications	47.9%

In the past, most of the focus was on geosynchronous satellites. Today large constellations of LEO and medium earth orbit (MEO) satellites are emerging. Hence, a broader range of GEO/MEO/LEO offerings is available. Future systems will use a mix of these orbits or orbital constellations. Many architectures are possible—wide area network–like configurations, for example, where LEO/MEO satellites act as servers and GEOs provide multicast services.

Consolidated communication networks, including both space and terrestrial systems, will offer many advantages: the user has full access to satellite and terrestrial content and network connections, and consolidation escapes the limitations of satellite- or terrestrial-only systems and provides for expansion of local terrestrial services to national and global capability.

Akin to consolidated communication networks, the evolving commercial space-imaging industry will combine the products of very high resolution, localized aerial photographers (0.25 to 0.33 meter) with wide-area surveying capability of upcoming U.S. space imagers, such as IKONOS (0.5 to 1.0 meter). IKONOS is the first satellite to be developed by Space Imaging L.P. (major partners are Lockheed Martin and Raytheon). These products, when further combined with the coarser imagery of Indian and French space imagers (5-meter resolution), can provide the full range of resolutions needed from cityscapes to mountain ranges at various angles of incidence. The 10 largest aerial photography organizations are already working with Space Imaging L.P. through Mapping Aerial Partners to digitize their film products, thereby enabling the creation of variable-resolution, high-quality raster imagery. Just as in the case of communications, the high-quality raster imagery from commercial space imaging can complement the national providers in furnishing value-added data to the infosphere of future battlefields.

Commercial communication satellites are undergoing rapid changes driven primarily by the demand for higher data rates. Spectrum overcrowding is pushing the industry to higher frequencies (Ka-band) and multiple beams to achieve frequency reuse. On-board routing, including asynchronous transfer mode protocols, will direct voice and data between multiple beams deviating from the conventional bent-pipe transponder configuration. Multiple, steerable spot beams with reconfigurable coverage will replace fixed beams. Constellations at all orbits will use laser intersatellite links. Programmability will facilitate bandwidth on demand, reconfigurable antenna patterns, etc. In general, satellite prime power will continue to increase. In the case of geosynchronous satellites, the power level has been doubling about every 5.5 years with attendant weight increase. This will place increasing demands on launch vehicles.

The industry remains intensely driven by competition to continually reduce cost and cycle time. Unique designs to satisfy a single customer are being supplanted by mass customization techniques. Standard building blocks are configured to achieve unique requirements. Modular units and subsystems are employed to enhance manufacturability. Plug-and-play techniques facilitate interoperability. The objective is to achieve a balance between manufacturing economies of scale and satisfying unique customer requirements. Dramatic improvements have been demonstrated. The price of commercial communication satellites has declined approximately 8 percent per year for the past 10 years, excluding added functionality and complexity. Cycle times have decreased from more than 3 to less than 2 years.

7.1.2 Buying Commercial

The Air Force can realize substantial cost savings and shorter cycle times by the prudent use of commercial buying practices. Arguably the biggest impediment is the behavioral changes required.

7.1.3 Radiation or Threat Impacts

While LEO satellites are very susceptible to damage and permanent degradation from modest nuclear bursts, today's commercial geosynchronous satellites are surprisingly able to survive even in the presence of a significant nuclear explosion. Long-life geosynchronous buses, such as the HS 702 or A2100 series, may be able to survive a 1-megaton explosion below GPS altitudes without permanent damage. Their operation may be disrupted, but with the help of ground intervention they could be brought back into service in a couple of days. LEO satellites, on the other hand, would be rendered useless in a matter of a few days after such an event even if they were not in the line of sight of the detonation. Replacement LEO satellites would be impractical for 1 to 3 years due to the slow decay of the enhanced radiation environment.

Satellite bus and payload suppliers might consider making provisions for nuclear hardening if the Air Force were to establish stable and reasonable threat requirements. Provisions might include allocation of space on circuit boards for added current-limiting devices and/or providing volumetric clearances for the later addition of systems-generated electromagnetic pulse (EMP) connectors. A reasonable incentive for the suppliers might simply be the knowledge that these provisions would enhance their business opportunities with the Air Force.

7.1.4 Technology Improvements in the Future

LEO and GEO satellites are becoming progressively larger. Higher data rates and lower-cost ground terminals are driving development of communication satellites while higher-resolution, multispectral-capable, agile vehicles are driving development of remote sensors. The increase in size is driven by the rapid increase in power requirements together with computational and data storage demands. The corresponding technologies with high leverage are shown in the table below.

Table H-5. *High-Leverage Spacecraft or Bus Technologies*

Subsystem	*Near Term <5 years*	*Medium Term 5–10 years*
Spacecraft Power	• 3x improvement in energy storage density • High-efficiency (40%) solar cells	• 6x improvement in energy storage density • High-efficiency (50%) solar cells
Command & Data Handling	• 64-bit radiation-hardened processor • 64-Mb radiation-hardened memory • Radiation-hardened fiber-optic data bus components (Megarad)	• Holographic data storage • Optical processors
Attitude Control	• Radiation-hardened star trackers	

7.2 Bus Acquisition Concepts

7.2.1 A Robust Commercial Market Can Benefit the Air Force's Satellite Bus Needs

The Air Force can realize lower costs and cycle times by leveraging the commercial satellite industry. Often a unique satellite requirement can best be met by adapting an existing commercial bus to a unique military payload. However, the notion that one bus can satisfy all payload requirements is unreasonable, at least by today's standards. The issue is interdependence between bus and payload. For example, the interface must consider power requirements, electrical connections, attach points, sensor view factors, center of gravity, and coupled loads analysis. These are relatively straightforward considerations, but most existing buses must undergo some modification to accommodate a given payload. The interface considerations could be simplified if the Air Force established a minimum set of unique bus requirements beyond standard commercial practices. In fact, it is likely that the industry would "design in" or make provisions to facilitate subsequent modifications to provide for these needs if these requirements were perceived as reasonable. It is equally important that the requirements remain constant over time.

7.2.2 Government Can Benefit From Commercial Acquisition Practices

To take full advantage of the potential cost and cycle time benefits of adapting a commercial bus with a military payload, it is important to employ commercial buying practices. Arguably the most important is to assure known or firm functional requirements at the outset. This implies extensive dialogue with potential contractors to perform trades. The primary objective is to achieve a prudent balance between cost and performance by maximizing the use of existing commercial designs. The Government should avoid striving for perfection and squeezing the last ounce of performance out of a design at the expense of margins. Midstream requirements changes must also be avoided.

A firm fixed-price contract is most appropriate when risks are manageable. This type of contract encourages thorough requirements development and minimizes requirements creep during the contract. Also, this form of contracting tends to stabilize funding relative to congressional action.

Virtually all commercial satellite contracts employ milestone payments as opposed to progress payments. This payment method gives the contractor an incentive to meet the scheduled milestones. Generally this method of payment is more cash-favorable for the contractor, but provides the customer with a powerful means to assure that the program stays on schedule.

Adopting commercial buying practices within the Air Force is a challenging task. The difficulty is not the mechanics per se but the associated behavioral changes required. The purpose is to get people to focus on justifying the use of commercial products rather than rationalizing why the products are inappropriate or striving for a reasonable balance between performance and cost ("the business case"). We recommend that the Defense Systems Management College include within its curriculum a module on commercial buying. Case studies contrasting government and commercial practices applied to a specific program might be very effective.

7.3 Radiation Hardening

7.3.1 Radiation Effects

Commercial satellite suppliers provide buses with vastly different radiation and upset susceptibility for geosynchronous and LEO applications. LEO buses in general have a 10– to 15–KiloRad silicon equivalent (krad$_{si}$) total dose capability. The corresponding total dose capability for long-life, geosynchronous orbiting satellites is in the 100- to 200-krad$_{si}$ range. The difference is in part due to design life (a factor of 2 or more), but mostly to the difference in the expected environment. The relative mildness of the LEO environment, combined with the need for very low unit recurring cost, forces contractors to use radiation-soft parts. In contrast, GEO satellites with 15-year life require total dose capability on par with threat-hardened military satellites. The total dose requirement of Space-Based Infrared System (SBIRS)–High due to the total effect of 12 years of life and defined threats is about the same as the total dose requirement of the commercial bus that the satellite was derived from.

Commercial satellites' susceptibility to single-event upsets is protected by both *hardware and software.* Burnout protection is provided at the circuit level. Logic change (bit flip) is protected against by voting logic, parity checks, etc. GEO satellites tend to have much more thorough protection than LEOs due to differences in the environment.

Commercial GEO satellites have inherent hardness that enables them to survive nuclear bursts on the order of 1 megaton at GPS altitudes, even when they are in line of sight. These satellites may require subsequent ground intervention to reset or reboot processors, but otherwise would suffer no permanent damage. This statement assumes that they have some read-only memory (ROM)–loadable safemode capability—as many satellites do—that would take attitude control of the satellite after the event. LEOs, in contrast, would have a very short life, even if they were not in the line of sight of the burst source at the time of the explosion. Iridium might survive only for several days after a burst and could not be replaced by a satellite with a reasonable life expectancy for as long as a year or more.

7.4 Technology Needs of Buses

7.4.1 Power Generation and Storage

Communication spacecraft bus costs are primarily driven by power subsystem costs. Even for a modestly powered communication satellite (4 to 5 kilowatts), power generation costs are approximately $500 to $600 per watt (W) with a power density of about 75 to 80 W per kilogram (kg) for rigid arrays and about 50 to 70 percent higher power density for flexible arrays. The technology goal is to reduce power generation cost to $300 per W with a corresponding (rigid array) density value of 300 W/kg (in 1997 dollars). The technologies that offer the best prospects to achieve these goals in the near term are very high efficiency (35 to 40 percent) solar cells. These would have production costs on par with today's gallium arsenide (GaAs) cells on the basis of an end-of-life power generation.

Power storage will rely on chemical devices (batteries) in the near term. Today's NiH batteries will have to be replaced with the much more efficient Li-ion batteries, particularly the polymer type. Battery energy densities need to be increased from 40 Watt hours (Whr) per kg to 100 or 125 Whr per kg. In terms of cost, the present cost ($100 per Whr) is unlikely to be reduced by more than 20 percent. Li-ion (liquid) is likely to reach the goal of 100 Whr per kg in the near term, while the polymer variety may reach 125 Whr per kg in 5 to 6 years. Flywheel technology could provide a marginal improvement over these values in the longer term. However, it offers the additional advantage of combining attitude control with power storage and thus providing additional weight and cost savings. Flywheel technology for long-term missions is still 10 to 15 years away. Even if it is proven at the device level, a number of system issues need to be answered in terms of redundancy management, failure management, spin-up, etc.

7.4.2 Data Processing and Advanced Memory Devices

In the past 10 years, radiation-hardened processor throughput increased from 3 to 30 millions of instructions per second as the industry moved from MIL-STD-1750A processors to 32-bit processors. The increased demand for data compression, on-board processing, autonomous operation, higher pointing accuracy, etc., creates a high demand for more computational capability. The demand will require a 64-bit space-qualified bus processor, which does not yet exist.

The current generation of radiation-hardened random access memory (RAM) components is based on the 1-megabyte (Mbyte) chips available from Honeywell and Lockheed Martin Federal Systems (LMFS). These are the most voluminous and costly components in a spaceborne data system. This technology is far behind the level of integration available in the commercial industry. LMFS is developing a 4-Mbyte memory chip. Development of 64-Mbyte memory chips is essential for future missions.

In addition to the RAM chips, solid-state recorders will require dramatic improvement in integration density. This is driven by the future needs of remote-sensing satellites with multi- and hyperspectral instruments, which can accumulate a vast amount (several terabytes) of data between downlink opportunities from LEO. Current multiterabyte recorders weigh 600 to 700 pounds. There is a need to reduce this by an order of magnitude. Memory technologies, such as holographic memory storage, offer opportunities for such savings.

The high-data-rate optical data bus, AS-1773, running at 20 megabits per second (Mbps) or higher, is not radiation-hardened for GEO satellite applications and not able to survive nuclear threats. The optical components in AS-1773 are based on 1,300-nanometer wavelength technology. Neither the fiber nor the optical transceiver devices are able to survive radiation requirements at present. There is a need for an optical serial data bus to handle data traffic for the following reasons:

- High-data-rate capability
- No transient electromagnetic pulse emanation standard (TEMPEST) concerns
- No EMP concerns

We recommend that AFRL complete the development or qualification work started in the early 1990s by Sandia National Laboratories and the Goddard Space Flight Center.

7.4.3 Impact of GPS

The use of GPS for navigation in LEO is now an accepted practice. Space Systems Loral pioneered the use of GPS for attitude determination of LEO satellites. Lockheed Martin Missiles and Space is developing a radiation-hardened GPS receiver for GEO applications with an incomplete GPS constellation set. The next step is to develop a GPS-based attitude-determination system for geosynchronous applications. This would be an enabler for small, low-cost satellites flying in formation to fulfill a very sophisticated mission.

While private industry would certainly develop the required receivers, the Government needs to provide GPS signals from the constellation to GEO altitudes. This requires an additional GPS antenna pointing away from earth toward the GEO vehicles above.

7.4.4 "Formation" Flying (Distributed Function Satellites)

For a typical geosynchronous commercial communication satellite, launch vehicle service represents at least 30 percent of the total deployment cost. Availability of launch slots is a key parameter in the business plan. With the arrival of very low cost access to orbit, a new generation of space architectures could exploit the absence of launch cost as a significant factor in making the business case. At $500 per pound to LEO, or $1,500 per pound to GTO, the possibility exists to break up a given mission into a number of cooperating satellites launched separately over time to better tailor the capacity to the market and to provide replacement or enhancement down the line. The "formation" might be interconnected in space or through ground elements. The satellite might replicate functions or distribute them among the formation members.

The technologies, needed to support formation flying, are:

- Autonomous orbit management for very large constellations
- Local GPS systems
- Low-cost intersatellite link
- High-performance computing

7.5 Recommendations

7.5.1 Satellite Bus Acquisition

- Adapt commercial satellite buses to meet needs where practical.
- Establish a minimum set of unique bus requirements beyond standard commercial practices (for example, radiation hardening, telemetry and command protocols, and autonomous operation). Work with industry to make the right choices and assure that the requirements remain stable over time.
- Gain commercial buying expertise for developmental items (such as satellite buses) with manageable risk. Incorporate commercial contracting into the Defense Systems Management College curriculum. Charter Space and Missiles Systems Center (SMC) to become the commercial buying expert for satellite buses.

7.5.2 Technology Investments

Near- and medium-term technology investments should focus on:

- Improvement in energy storage density by a factor of 2 to 4
- A doubling of solar cell efficiency (watts per kilogram) while improving power generation efficiency (cost per watt) by a factor of 3 to 4

7.5.3 Radiation-Hardening Recommendations

With the need for space-deployed information networks, there is a need for a new generation of radiation-hardened processors based on a 64-bit architecture to replace present 32-bit technology. To enable the efficient flow and storage of on-board information, there is a need for greatly increased memory storage capability:

- Radiation-hardened, terabyte mass storage devices of sugar cube size
- 64-Mbyte RAM chips
- Radiation-hardened, high-speed (20 Mbps) fiber-optic data buses

While the commercial communication satellite industry would be highly resistant to legislated hardening requirements, the proper incentives could induce them to build in protection or provide hooks for it. The industry could be given incentives to undertake this in hope of future governmental business. The necessary preconditions for such voluntary undertakings are as follows:

- Establish reasonable requirements

- Work with industry to establish the requirements
- Keep requirements stable

8.0 High-Leverage Technologies for Air Force Investment

8.1 Materials and Manufacturing

Materials and manufacturing form the foundation of effective, low-cost vehicles and propulsion. In particular, space operations demand lightweight, low-cost manufacturing since expendable vehicles are discarded without reuse. For reusable vehicles, low cost is still important because the vehicle development and production costs must be amortized over the life of the vehicle. Three areas appear to be important for near-, mid-, and far-term space vehicle development. These are:

- Efficient low-cost manufacturing
- Controlled, adaptive structures (including health management)
- Low-cost efficient materials

Manufacturing processes for commercial products are in flux. Techniques such as “manufacturing by light” (in which powdered materials are converted by laser energy into formed parts that minimize waste) have high strength and fewer parts. These techniques promise to reduce manufacturing cost and increase product reliability. These processes are particularly important for the construction of lightweight, low-cost rocket engines.

8.1.1 Advanced Composites (Midterm)

A number of advanced composite materials have great promise in the midterm future for spacecraft and launch vehicle structures. These include metal matrix composites (such as titanium matrixes) and discontinuously reinforced metals (including titanium and aluminum). Over the longer term, use of metallic or graphite foams could prove very promising. Large-scale vapor synthesis with atomic or molecular control of nanocrystalline structures, perhaps with computer-designed woven or braided synthetic reinforcements, promises to have large effects on the weight of space structures. Coupled with health-monitoring sensors such as micro-electro mechanical system devices and the ability to heal failing structures, advanced composite materials will also improve longevity and operational reliability.

8.1.2 Atomic Bond Structures (Long Term)

It has long been known that if materials could be made entirely or principally of atomic bonds, their use would enable major decreases in the weight of structures. A number of possibilities have been identified; though probably only applicable in the long term, they nonetheless are extremely promising. Leading among these are carbon nanotubes, or “Buckytubes.” Although these materials are in the very early stages of laboratory research, they have already been made in the form of long, thin, hollow tubes about .001 the wavelength of light in diameter and about 1 to 2 wavelengths long. Their overriding virtue is that since they have only pure carbon-carbon atomic bonds, they have a calculated strength-to-weight ratio 600 times greater than steel. They are being made in laboratories at the University of California, Los Angeles, and Rice University, and at the Naval Research Laboratory (NRL), at rates of up to pounds per day, at reported yields of up to 90 percent. If laboratory research could be focussed on how to assemble many such Buckytubes into long fibers by connecting their ends, or by overlapping the tubes with carbon-carbon atomic bonds using a combination of controlled heat, pressure, and catalysts to induce the bonds to form, the result could be superstrong strings, mats, rods, and sheets of pure Buckytube materials.

If such materials could be affordably manufactured on a large enough scale, they could be used for all structures, cases, attachments, engines, tanks, electronic circuit boards, etc., of launch vehicles and spacecraft. They have potential to reduce the structural weight of everything by factors up to several hundred. Thus, structures made from carbon nanotubes, or other similar materials with purely or principally atomic bonds, could result in spacecraft with only a fraction of today's weight, and launch vehicles with a fraction of today's launch costs. Such reductions could clearly revolutionize all space operations. Atomic bond materials in general, and Buckytubes in particular, are in an early research stage. Due to their potential for the long term, the Office of Scientific Research/AFRL materials programs should consider funding research in this area to eventually produce practical and usable materials for structures.

8.1.3 Actively Controlled Adaptive Structures

Controlled adaptive structures include a wide variety of structural concepts that will have useful application to space vehicles. These applications include acoustic load control inside space vehicles at launch, adaptive shaping of mirrors and antennas, and reconfiguration and load control to account for structural damage. These concepts not only reduce weight, but also contribute to the reliability of the system being controlled. Perhaps the most important near-term and midterm application of controlled structures is health management or health monitoring, which involves continuous sampling of structural characteristics to assess the state of the structure. For instance, we may want to identify the load spectra for individual components or detect damage and monitor its growth to the point where it needs repair, either on the ground or in flight.

8.1.4 High-Strength, Radiation-Resistant Tethers

Tethers are extremely versatile, enabling many unique applications. These include power generation, maneuvering and changing orbits without propellants, deploying payloads from launch vehicles, forming large constellations without requiring propellants or compression members, and rotating two spacecraft about each other so as to prevent orbit determination or interceptor targeting.

Tethers have been tested in space 16 times, and the latest one has been in orbit more than 1 year. These tethers can now exist in orbit for decades because of the invention of a patented multiline redundant design. Their performance for many military applications would be enhanced by materials that have high resistance to micrometeoroids, higher strength-to-weight ratio, low optical and longwave infrared signature to decrease their visibility, resistance to abrasion, durable high-voltage insulation, and other beneficial characteristics.

8.1.5 Thermal Protection Systems

Development of new materials is always of interest. Space operation has more particular requirements than air vehicle operation since it requires both high- and low-temperature operation. For instance, we need lightweight, thermal protection materials to make low-cost reusable vehicles a reality. Current materials are so heavy that their weight may be of the same order as the load carrying structure itself. Since propulsion systems drive the design of both expendable and reusable vehicles, high-temperature materials that are lightweight and easily manufactured into rocket engines are important. Materials for extremely low temperature liquid hydrogen and liquid oxygen tanks are also necessary. Research for metallic and nonmetallic materials that can contribute to these objectives is important.

8.2 Propulsion Systems

8.2.1 Pulse Detonation Wave Engines

The Pulse Detonation Wave Engine (PDWE) is an intermittent combustion engine (either airbreathing or nonairbreathing) that relies on unsteady (pulsating) detonation wave propagation for combustion and compression elements of the propulsive cycle. While specific configurations vary, in general the PDWE consists of propagating detonation waves generated periodically within an engine tube. The associated reflected expansion waves act periodically to draw in propellants without pumps while producing high forward thrust. The PDWE concept holds real promise for high-thrust-density, low-fuel-consumption space propulsion applications, ranging from boosters and upper stages to microscale propulsion for spacecraft. Advantages of the PDWE include significantly reduced numbers of moving parts, a high thrust-to-weight ratio (no high-pressure pumps or compressors), low-cost modular design possibilities, and high potential performance for a wide range of fuels (gaseous or even liquid). A number of alternative configurations for the PDWE have been proposed and tested, yet only low-level government funding for the PDWE has been provided to date through the NASA and Air Force Small Business Innovative Research programs.[6]

Associated with successful development of the PDWE are critical issues or goals requiring Air Force investment:

- Understanding and being able to accurately model and simulate the complex underlying physical mechanisms governing the behavior of multidimensional, unsteady detonations and related phenomena such as deflagration-to-detonation transition
- Developing methodologies for the closed-loop control of the PDWE
- Developing robust (at high temperature or pressure), real-time sensors to enable implementation of these control strategies
- Using these computational or control tools in the development of design methodologies for the PDWE

Noise reduction, structural loads resulting from oscillatory combustion, and other integration issues are also potential barriers. Strong basic (6.1) as well as applied (6.2) multidisciplinary research is needed in this promising technology area.

8.2.2 Combined Airbreathing/Rocket Engines

While airbreathing engines have significantly higher specific impulse (Isp) potential than rocket engines at lower flight speeds (less than Mach 12), drag penalties and lower thrust-to-weight ratios for airbreathing engines have to this point made them impractical for space launch. Yet when combined with a chemical rocket as in the rocket-based combined cycle concept, airbreathing engines (ramjet-scramjet) offer the potential for improved payload fraction, lowered cost per pound to orbit, and increased reusability when compared with an ELV. Alternative configurations that reduce the use of heavy turbomachinery in a combined cycle include the liquid air cycle engine concept, in which the incoming airflow is condensed (and is pumpable using a much smaller compressor) using on-board cryogenic propellants with heat exchangers. Such concepts are in fact being explored to a much greater extent in Japan and Russia. Though industry and NASA do not yet agree on the eventual magnitude of benefit due

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[6] "Pulse-Detonation Engine Workshop," sponsored by the Office of Naval Research, Naval Postgraduate School, Monterey, CA, 10 October 1997.

to combined-cycle propulsion, it is possible that these engines may hold significant benefit for some Air Force missions and deserve technology investment and development by the Air Force.

As noted, purely airbreathing engines (ramjets and scramjets) do not appear feasible for launch of orbital payloads, yet they do have the potential for suborbital transport or transfer that could provide the Air Force with significant warfighting capability. Recent advances in combustion modeling and closed-loop control strategies for high-speed combustion systems, in concert with NASA's Hyper-X program, could make scramjet engine development a reality. Thus, despite recurrent (and perhaps not highly successful) efforts in the past to develop hypersonic vehicles, at least a low level of support by the Air Force should be maintained for scramjet development to leverage the NASA investment.

8.2.3 High-Energy-Density Propellant

The chemical propellants in use for rocket-based space lift were developed over 30 years ago and clearly are confronting technological limitations in terms of Isp and thrust-to-weight. While the Air Force has had some level of research effort in developing high-energy-density propellants, significant increases in Isp (by 200 or even 800 sec) and reductions in launch costs (below $100 per pound) could be realized by taking advantage of highly energetic atomic materials such as cryogenic solid hydrogen and oxygen and metallic hydrogen (for example, hydrogen atoms in a dissociated metallic state). The recombination energy of highly energetic atomic ingredients such as boron, carbon, and lithium could be exploited, for example, through packaging of these materials in cryogenic solid matrices so that their molecules would be physically separated from one another by hydrogen host molecules. In order to make cryogenic solid propellants technologically feasible for implementation in launch systems, however, significant advances in the areas of spectroscopic characterization of species, computational modeling of the energetic additives, methods for handling and transport, and methods for production or manufacturing need to be made. While realizing that the goals of significantly increased Isp and thrust to weight via high-energy-density propellants may take place a decade or more in the future, the Air Force is well equipped to undertake and support this type of focused, long-term research.

8.2.4 Hydrogen Storage in Buckytubes

Recent laboratory experiments and theoretical work indicate that Buckytube materials can adsorb or absorb large quantities of hydrogen gas and store them at room-like temperatures and pressures. Upon heating, the gas is released. Small-scale experiments indicate that storage densities equaling that of liquid hydrogen are probably attainable. One laboratory claims densities 10 times greater, though the results have not been confirmed and may not hold up.

This method of hydrogen storage is being pursued in Germany for fuel cells for cars and submarines, where weight is secondary to volumetric efficiency. For rocket vehicles, weight efficiency is paramount; thus the weight of the Buckytube matrix itself must be considered if the technique is to be useful compared to liquid hydrogen tanks. In this case, the densities must be about 10 times that of liquid hydrogen to compare favorably, which is problematic.

The possibility remains real until disproved, however, and since the payoff would be revolutionary for launch vehicles, research should be rapidly directed toward that end.

8.2.5 Magnetically Levitated Catapults

The magnetically levitated catapult is a relatively near-term technology that could be used to provide energy assist to the launch vehicle. Relatively little research effort within DoD or NASA has been expended on this technology despite the promise shown by Japan's near-term implementation of magnetically levitated rail systems. The generic magnetic rail system for space launch could consist of a mile-long evacuated track oriented at 45 degrees at an elevation of 10,000 feet. Launch of a magnetically levitated vehicle from this type of track could be accomplished at Mach 1, effectively doubling the payload capability of a rocket-based RLV. This type of launch assist is being studied at NASA Marshall Space Flight Center. Its very low energy and other operations costs may almost halve the cost per pound of payload of any launch vehicle so boosted.

8.2.6 Blast Wave Accelerators

A new development makes the possibility of a global-range, precision-strike weapon a distinct possibility. Though various guns have been investigated for launch into space, including various ram accelerators, electromagnetic accelerators, and gas guns, none appear as promising as a solid-propellant synchronous ignition concept that recently emerged from Russia. It employs a large number of narrow annular explosive rings placed axially along a barrel. A payload is accelerated by properly timing the explosion of the rings so as to maintain constant high pressure on the payload. One option does not even require a barrel.

Models and experiments indicate that orbital velocity can be reached in a 120-foot gun at an acceleration of 100,000 grams or in a 40-foot gun at 300,000 grams. Payloads of 1,500 pounds are shot into suborbital trajectories with global range. If the payload comprises a properly designed smart bomb, guided by GPS or with a homing seeker, a precision-strike weapon is realized. The estimated costs of launch are only $60 per pound of payload. The gun can be sited in the continental United States or other rear location and can be rapidly refurbished for fast turnaround. Liquid injection techniques exist to reduce the thermal input to the smart bomb during both ascent and reentry.

This weapon could be manufactured very inexpensively, with only $15 million estimated for an emplacement. Use of such a weapon would reduce the exposure of crews to harm, deliver a large number of strikes very rapidly and inexpensively with complete surprise, and avoid many problems of space-basing strike weapons. It could be seen as a competitor to some of the missions of the AOV system, but is not as flexible or capable, and cannot eliminate the need for the AOV.

According to a University of Texas–Austin researcher, Dennis Wilson, a proof-of-concept demonstration could be fielded for about $0.2 million, a half-orbital velocity system for about $1 million, and an orbital velocity demonstrator to launch a 1-kg payload for about $3 million.

8.3 Tethered Orbital Accumulator

A reversible conducting electromagnetic tether extended along the local vertical from a spacecraft can function either as an electrical generator or as an electrical motor. In the generator mode, power is obtained at the expense of orbital altitude, while in the motor mode, electricity supplied from solar arrays causes the orbital altitude to increase.

If this system is used to raise altitude when the spacecraft is sunlit, and used for power generation when in darkness, it functions as an orbital energy accumulator. This is exactly the same overall function performed internally by a battery, reversible fuel cell, or flywheel. The big advantages, however, are that it has 100 percent depth of discharge, nearly 100 percent conversion efficiency, no life-limiting mechanisms identified, and higher energy density than any of these alternatives.

This near-term energy storage and conversion subsystem technique offers so many potential advantages in weight and cost that the Air Force should investigate its employment on mission spacecraft in the near future.

8.4 Optical Systems and Sensors

8.4.1 Stationkept Swarms of Coherent Elements

A particularly powerful technique is to use many stationkept elements to replace the structures of large antenna and optical sensors with information. Very many loosely stationkept elements, each of which controls its phase or time delay so as to cause all the signals to add coherently, can behave as though their positions lay along a perfect plane or parabola in space. This ability leads to fundamentally new and powerful capabilities: to implement arbitrarily large antennas and radiofrequency apertures with very low weight and no structures at all.

The resulting apertures could be almost filled if the elements were stationkept to the point of almost touching, or the aperatures could be sparse if stationkept far away from each other to make very large arrays. For optical telescopes, the elements would be adaptively controlled membrane primaries and secondaries, all stationkept with respect to an assembly containing a liquid-crystal corrector for each primary element. Coherent antennas, tens of kilometers across, and optical sensors, 100 to 200 meters across, are possible.

This concept, as well as that in the following section, were proposed by Mr. Ivan Bekey and based on studies he performed for the Aerospace Corporation.

8.4.2 Large Adaptive Membranes for Antennas and Optics

Inflatable antennas and optics are being pursued because of their promise of becoming very low weight deployable large apertures. Current approaches use inflatable plastic films and depend on mechanical and pressure accuracy to attain and hold a desired figure to a required accuracy. A much more powerful technique is to make the entire membrane surface adaptive and control it so as to attain and maintain the desired figure as well as eliminate small-scale errors in a closed-loop mode.

This can be done by coating the back of the reflective membrane with a motor film such as a two-layer piezoelectric bimorph, a nitinol film, or both, and controlling the surface shape by actuating the motor layer by irradiating it with an external energy source. This source can be a scanning laser or electron beam with spatial energy deposition modulated in response to a real-time figure sensor. The figure sensor would generate a signal responsive to the deviations of the surface from the desired shape. This technique allows control of the fine-scale surface irregularities as well as the gross figure, attaining high surface accuracy and flexibility while retaining the light weight of inflatables. The laser or electron gun and the feed assembly can be stationkept with respect to the membrane, avoiding all structural trusses.

For optical telescopes, a second stage of correction is required. It can be a liquid crystal at a reimaged location, with a hologram of the primary surface errors impressed on it. The responsive variation of the crystal index of refraction introduces the time delay required to correct the residual errors, enabling an optical-quality, large-diameter, lightweight telescope sensor. In addition, if all elements are stationkept with respect to each other, no heavy precision truss is needed.

Lightweight antennas of 100 to 300 meters in diameter usable to Ka-band, and optical telescope sensors to 20 meters in diameter weighing 100 times less than conventional glass mirror-precision truss designs, are likely.

Early liquid crystal correctors are operating on the bench at AFRL, Kirtland AFB, New Mexico. Active, adaptive membranes were investigated by the Jet Propulsion Laboratory, but are currently unfunded. The individual technologies, as well as the complete system require focused attention to realize the promise of this new concept.

8.4.3 Liquid Crystal Time-Delay Correctors

Liquid crystal plates are being researched at AFRL, Albuquerque, New Mexico, as wavefront correctors for optical telescopes. These plates are driven by a hologram of the errors in a primary mirror, and have the ability to correct a few tens of wavelengths of error. When combined with the adaptive membranes discussed above, they have the potential of implementing adaptive space telescopes that can easily be tens of meters across.

With such large telescope apertures, long dwell, or continuous high resolution, global ground imaging can be performed from GEO with just three spacecraft. Due to the extreme leverage of such applications, the current activities at AFRL should be supported but driven to investigate materials capable of correction of thousands of wavelengths of errors, even at the cost of slower response.

8.4.4 Advanced Health Measurement Sensor Technologies

Many of the technologies identified to achieve quantum improvements in space lift and spacecraft systems (for example, spatially distributed spacecraft swarms, development of health management systems, and advanced propulsion systems) depend on development of environmentally robust, small-scale, real-time sensors and actuators. In many of these applications, sensors and actuators will be required to operate in real time under very high temperature and pressure conditions, likely precluding the use of temperature-sensitive semiconductor active elements. Advances in the area of environmentally robust sensors (and, to a lesser extent, actuators) and materials therein are essential to the development of complex distributed systems recommended in this section. For example, Air Force investment in novel methodologies, such as wireless sensors with circuits based on high-temperature materials (such as ceramics) and passive radiofrequency circuits that provide direct detection of temperature and strain, could lead to development of compact sensing wafers for use in very harsh environments.[7] Such low-power, wireless sensors are at a rather embryonic stage, but nevertheless have tremendous promise for space lift and spacecraft technologies.

8.5 Distributed Systems Management

8.5.1 Health Monitoring, Redundancy Management

The objective of a health monitoring system is to produce ultrahigh reliability in the presence of less reliable components. To achieve this level of reliability, additional complexity is introduced in terms of additional hardware and software. One objective is to produce the required redundancy, in the presence of large system complexity, in a systematic manner. General methodologies do not exist, and current methods, which are ad hoc, seem quite limited in extending to more complex systems. However, the payoff for automated checkout of launch systems, fault detection, and fault handling during launch and for spatial arrays of microsatellites appears enormous and enabling.

8.5.2 Health Monitoring for Time-Critical Failure

For time-critical failures, rapid and reliable fault detection and identification methodologies must be coordinated with fault-handling techniques. Although hardware redundancy is extremely effective, it is costly, adds weight, and can be applied only to components that are easily duplicated, such as sensors and actuators. Robust methodologies that relate dissimilar sensors and can detect and identify sensor, actuator, and plant faults through the system dynamics should improve overall reliability and reduce hardware cost and weight, although at the expense of software complexity. Once a fault has been

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[7] K. Bult et al., "Low Power Systems for Wireless Microsensors," Digest of Technical Papers, Proceedings of 1996 International Symposium on Low Power Electronics and Design, Monterey, CA, 12–14 August 1996.

identified, fault-handling methodologies that ensure system recovery must be developed to guarantee overall system stability. These schemes may require the reliable generation of the probability of a fault and the probabilities of a false and miss alarm.

8.5.3 Health Monitoring for Spatially Distributed Systems

An especially important health-monitoring task involves the automated determination of the integrity of highly pressurized composite tanks during the prelaunch phase. Delamination of small regions in the composite tank can lead to propellant leakage, which may cause catastrophic failures. The objective is to detect changes in the tanks' composite lamination before the defect leads to rupture sufficient to cause leaks, and then to identify the region so that the tanks can be repaired. This could be done by instrumenting the tanks with an array of sensors and actuators. The actuators would induce a spectral signature sensed and used to determine the integrity of the tanks and the location of the possible regions of delamination. This health-monitoring procedure requires online dynamic simulation of the tank, including the sensor outputs and actuator inputs. Methodologies that reduce dynamic complexity but capture the important dynamic structure enable real-time monitoring. Given the complexity of the composite structure and the *a priori* uncertainty of the failures, detection and identification schemes that allow for granularity may simplify the resolution of the extent and location of the fault. Hypotheses first might be constructed on a gross granularity and then refined. However, the determination of the integrity of the structure is predicated on the integrity of the distributed sensors and actuators. The coherence of the overall health monitoring system depends upon ensuring that the information used to detect and identify delamination is not corrupted.

8.5.4 Radiation-Hardened Fiber Optics

There are two types of optical serial data buses: one is MIL-STD-1773, and the other is AS-1773. The MIL-STD-1773 serial data bus runs at the same speed (1 Mbps) as the more common copper-based MIL-STD-1553. The high-speed (20-Mbps) AS-1773 being demonstrated by NASA unfortunately is not rad-hard for GEO satellite applications and (according to Lockheed Martin in-house evaluations) definitely not able to survive nuclear threats. The optical components in AS-1773 are based on technology operating at a wavelength of 1,300 nanometers. The fibers, as well as the associated optical transceiver devices, are not survivable at present. There is a need for an optical serial data bus to handle data traffic for the following notable reasons:

- High data rate capability
- No TEMPEST concerns
- No EMP concerns

Optical component radiation testing was performed for the Follow-on Early Warning System Program (precursor to SBIRS-High) for natural and nuclear environments in the 1992–1993 time frame. The natural environment results were published in the Institute of Electrical and Electronic Engineers 1993 Data Workshop Proceedings. At that time, the NRL and NASA/Goddard Spaceflight Center funded this work. A couple of important highlights showed that the indium gallium arsenide phosphide (InGaAsP) transmitters and receivers were very good with respect to total dose ionization, but could be sensitive to single-event transient upsets. High-dose-rate testing at Sandia National Laboratories showed that the fiber will darken and the 1773 components will upset.

The technology need is to continue the work done in the early 1990s and qualify high-performance AS-1773 components for the upcoming generation of high-data-rate military satellites.

8.6 Concluding Remarks

The technologies presented above are those with potentially high leverage to make major advances in launch vehicles and spacecraft for the next 10 to 20 years. These spacecraft can make revolutionary improvements to Air Force operations in allowing for ubiquitous and devastatingly effective force projection using space, and come much closer to the desired ability to "see everything, everywhere, at all times." Many of these technologies are in the "high-risk but high-payoff" category, in which investment can result in large improvements in capability for the Air Force.

These kinds of technology investments usually have a low priority in competition for funds in chronically short supply. However, the Air Force should find a way of protecting small but unusually high-leverage technology investments such as these.

8.7 Summary of High-Payoff Areas

- Investigate the possibility of replacing structural webs with information networks by using:
    - Adaptive membranes and liquid crystal correctors for large telescopes
    - Stationkept swarms of coherently cooperating elements for very large radiofrequency optical arrays
    - Highly reflective adaptive membrane mirrors in space for ground lasers
- Develop materials with 10 to 100 times the strength/weight, high-temperature atomic bond materials without matrix, for example, carbon nanotubes.
- Employ propulsion with high thrust/weight and high Isp simultaneously. Examples include the following:
    - Nonchemical, for example, magnetically levitated catapults and dynamic and electric tethers
    - High-energy-density propellants, for example, hydrogen storage in Buckytubes, metallic hydrogen
    - Blast wave accelerators (global range, precision-strike continental United States gun)
    - Highly reusable (more than 100 flights) chemical rocket engines, i.e., pulse detonation wave engine
- Apply pure-tension lightweight space structures such as tethers for maneuvering, power generation, antenna arrays, battery replacement, defensive countermeasures, payload deployment, and other applications.

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Annex to Appendix H

Acronyms and Abbreviations

AOV	Aerospace Operations Vehicle
AFB	Air Force Base
AFRL	Air Force Research Laboratory
CONOPS	Concept of Operations
DoD	Department of Defense
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
EMD	Engineering and Manufacturing Development
EMP	Electromagnetic Pulse
ER	Eastern Range
FAA	Federal Aviation Administration
FSD	Full-Scale Development
GaAs	Gallium Arsenide
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
GTO	Geostationary Transfer Orbit
I&M	Improvement and Modernization
InGaAsP	Indium Gallium Arsenide Phosphide
Isp	Specific Impulse
ISR	Intelligence, Surveillance, and Reconnaissance
Kg	kilogram
krad_{Si}	KiloRad Silicon Equivalent
LEO	Low Earth Orbit
Li	Lithium
LMFS	Lockheed Martin Federal Systems–Manassas
Mbps	Megabits per Second
Mbyte	Megabyte
MEO	Medium Earth Orbit
MIL-STD	Military Standard
NASA	National Aeronautics and Space Administration
NiH	Nickel Hydrogen
NRL	Naval Research Laboratory
O&M	Operations and Maintenance
PDWE	Pulse Detonation Wave Engine
RAM	Random Access Memory
RLV	Reusable Launch Vehicle
ROM	Read-Only Memory
RSA	Range Standardization and Automation
SAB	Air Force Scientific Advisory Board
S&T	Science and Technology
SBIRS	Space-Based Infrared System
SMC	Space and Missiles Systems Center
SMV	Space Maneuvering Vehicle
SSTO	Single Stage to Orbit
TDRS	Tracking and Data Relay System
TEMPEST	Transient Electromagnetic Pulse Emanation Standard

TSTO	Two Stage to Orbit
W	Watt
WR	Western Range

Appendix I

Terrestrial Segment

1.0 Introduction

1.1 Scope and Content

The Terrestrial Segment Panel was tasked to consider options for reducing the cost of acquiring and operating military ground systems. This involved addressing ground stations and equipment, human-machine interfaces, personnel and training, and interfaces between the military space ground environment and other military and civilian systems.

For the purpose of this study, we defined military space ground systems as consisting of the following areas, recognizing that roughly half the life-cycle cost of military space systems is currently entailed in these areas:

- Satellite Control. This includes the tracking, telemetry, and control (TT&C) functions needed to operate the satellite bus.
- Payload Management. This includes the management functions needed to operate the military payload carried on the satellite. This may (or may not) be functionally or physically separated from the satellite control system.
- User Terminals. This includes the user equipment needed to access space system services and support tasking and data processing of space-based assets.

Our recommendations and conclusions were based on the following premises, developed by the panel as our vision for the future of space operations and control. This vision evolved from meetings and discussions with operators of military and commercial space systems and users of the Air Force's current space services.

Commercial Systems. The military is no longer the primary developer or user of space systems. In particular, with the drive toward large constellations of low earth orbit (LEO) and geosynchronous earth orbit (GEO) commercial communication satellites, industry has far outstripped the Air Force in terms of the technology investment and the magnitude of the space systems currently being fielded. Unsurprisingly, we found that the industrial solutions being fielded were without exception based on improvements and enhancements to systems and procedures (and lessons learned) from the Air Force's space operations. In fact, many of these systems were being developed and operated by ex–Air Force personnel. The Air Force must learn to leverage these commercial developments to be able to recognize the same improvements in efficiency and operational effectiveness for military space operations.

Global Connectivity. The Terrestrial Segment Panel concurs with the network-centric vision for future military operations that has been explored by the 1998 U.S. Air Force Scientific Advisory Board (SAB) Information Management and Technology[1] Ad Hoc Panel as well as in the 1997 SAB Aerospace Expeditionary Forces (AEF)[2] report. The use of this Battlespace Infosphere can also lead to operational improvements and efficiencies in the management, tasking, and distribution of information from space assets. The development of a network-centric architecture will also enable backward compatibility with

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[1] U.S. Air Force Scientific Advisory Board study, Information Management and Technology, Ad Hoc Study, 1998.

[2] U.S. Air Force Scientific Advisory Board study, Aerospace Expeditionary Forces, Summary Volume, 1997.

legacy user equipment while allowing users to benefit from next-generation services in a seamless transition. This will result in cost savings by avoiding costly equipment upgrades for the operational users of these services.

Reforming Acquisition. The rapid pace of technology development being forced by the commercial space industry is resulting in shorter and shorter acquisition cycles. Commercial developers are dealing with this issue by moving to a spiral development cycle where planned upgrades continue throughout any program life cycle to enable operational efficiencies to be realized as new technology becomes available. Military space acquisition programs need to move to this model to be able to recognize the same benefits.

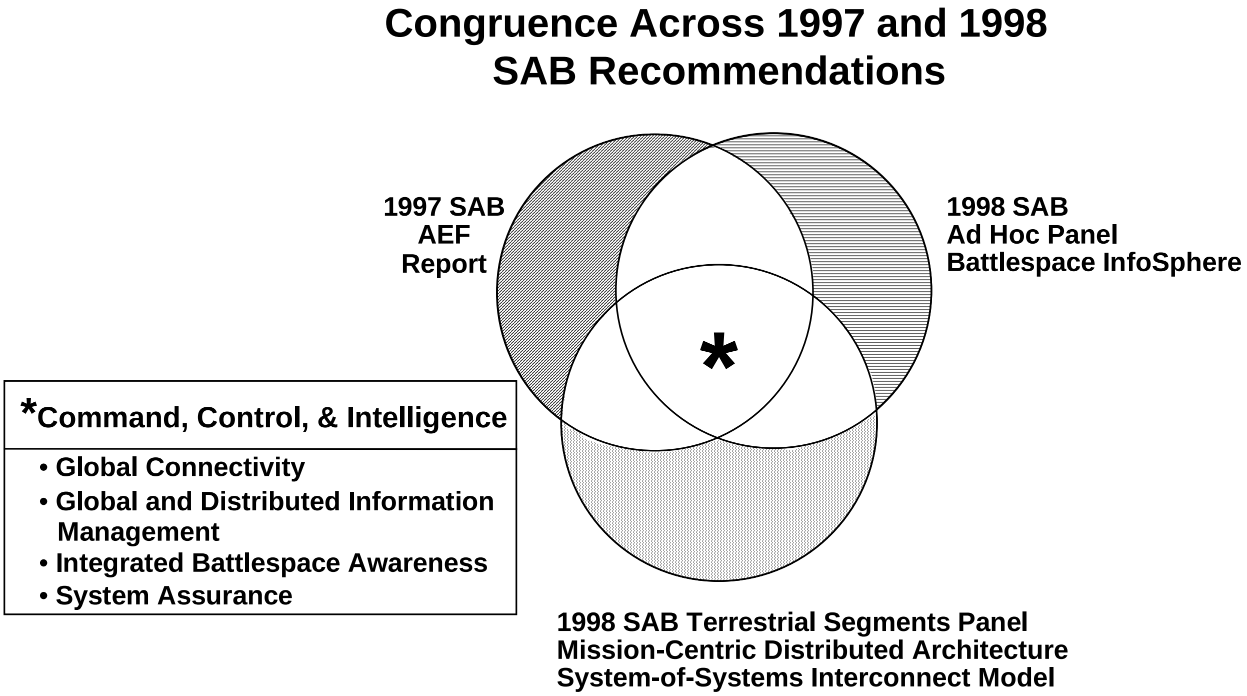

Figure I-1. *Mission-Centric Distributed Architecture System-of-Systems Interconnect Model*

1.2 Structure of the Appendix

In our study we considered options for reducing the costs of acquiring and operating ground stations by leveraging commercial satellite operations technology, practices, and services. The benefits that can be recognized through adopting commercial practices for satellite operations are described in Section 2.0.

The Terrestrial Segment Panel was tasked to consider issues associated with seamless integration of terrestrial segments into overall command and control (C^2) and combat operations, including ways to achieve needed responsiveness to warfighters at all levels of a force and in joint and combined operations. The panel evolved the vision of a mission-centric distributed architecture (MCDA) to accomplish this end (see Section 3.0), which would be built on a network-centric communications architecture (see Section 4.0) rather than relying on the current stovepiped approach for integrating space systems into military operations.

In order to leverage the rapid advances in commercial technology that will enable cost reductions in space operations, and to develop the information technology (IT) base that is needed to implement mission- (or capability-) centric rather than platform-centric architectures, the Air Force must adopt new types of acquisition practices. In Section 5.0 we describe the benefits of adopting a spiral development (SD) process to follow commercial practices for acquiring and developing space ground systems.

The panel also addressed the application of improved human factors in the acquisition cycle to result in improved operation and to lower required staffing and operator skill levels. The conclusion of these findings is outlined in Section 6.0.

In each section of this report, specific recommendations are given for implementation of the steps needed to recognize the benefits we have identified for modernizing the terrestrial segment of the Air Force's space operations. In Section 7.0 our top-level conclusions and recommendations are summarized as they pertain to the charter of this study.

1.3 Terrestrial Segment Panel Membership

Dr. Alison K. Brown, Chair
President
NAVSYS Corporation

Mr. Harry P. Arnold
Executive Vice President, Engineering
Boeing Commercial Airplane Group

Dr. Curtis R. Carlson
Executive Vice President
David Sarnoff Research Center

Mr. Jeffery B. Erickson
Manager, Crew Systems
Boeing Information, Space, and Defense Systems

Dr. John P. Howe, III
President
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Mr. Marshall A. Caplan
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Hughes Space and Communication

Dr. Richard F. Gabriel
Independent Consultant

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Mr. Wesley L. West
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Lt Col Walter C. Hess
Deputy Chief, Satellite Control Network Branch, Directorate of Requirements
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Col Charles O. Cornell
Director, Information Superiority
NRO/COMM

Lt Col Joseph O. Chapa
Chief, AWACS Systems Architecture and Engineering IPT
ESC/AWW

Executive Officer: Capt Douglas E. Cool, ESC/ZJC
Technical Writer: Maj Jeffrey E. Haymond, USAFA

2.0 Commercial Practices for Satellite Operations

2.1 Introduction

Modern commercial systems and practices for satellite operations are substantially more cost-effective than Air Force system operations. A comparison that is sometimes cited is that the Air Force has about 2,000 people operating about 100 satellites, whereas Iridium, a new commercial system, has about 200 people operating 60 satellites.

The issue is in fact more complex and far more important than just the number of people the Air Force devotes to satellite operations. This appendix presents a summary of our study, along with our conclusion that the Air Force will not be able to effectively support future satellite operations without better use of commercial capabilities and practices.

2.2 Comparison of the Air Force and a Modern Commercial System

The problems faced by the operators of the current Air Force satellite operation system are illustrated by a comparison (see Table I-1) of some key characteristics of the infrastructure and operating practices of the Air Force system (see Figure I-2) with Iridium (see Figure I-3). Although these two systems are quite different, the comparison provides insight into the principles of system design and operating practices that have evolved in modern commercial systems.

Table I-1. *Comparison of Satellite System Factors and Characteristics*

Air Force Satellite Control Network	***Iridium Network***
Multiple types of satellites with multiple missions • Some high-value, special-purpose satellites	Single satellite type with single mission
“Stovepiped” system • Ground and space hardware are often system-unique • Satellite TT&C and mission control are usually linked	Overall coherent system design, driven by business decisions • Spiral development, including operators • Continuous software upgrades and technology insertion
Requirement for extremely high reliability in all components • Major cost driver	High reliability achieved by system design • Lower individual component reliability • Component failures expected and planned for
Large infrastructure in U.S. bases and worldwide ground stations • Necessary in ’60s and ’70s	Space cross-links allow less reliance on ground network
Human-machine interface (HMI) usually poor; human factors not explicitly involved • Poor user software • People do repetitive tasks	Some emphasis on HMI • User-friendly hardware and software • Automation for repetitive tasks
High personnel turnover • Uniform military staff for most positions	Stable workforce • No problems with permanent change of station • Many personnel are former Air Force space operators
Archaic technology • Most TT&C uses ’70s technology (mainframe Jovial)	State-of-the-art technology, free of legacy infrastructure
Costly and difficult upgrades and capability increases • System design (software and hardware) complicates changes • Process is very slow, bureaucratic, and political	Recapitalization plan • Short budget cycles for technology insertion • 5-year satellite replacement to upgrade technology
	Plans and funding in place for major capability increase • Global Positioning System–based orbit maintenance • Iridium Next: capacity and data rate 50x Iridium • Teledesic/Celestri: capacity and data rate 10,000x Iridium

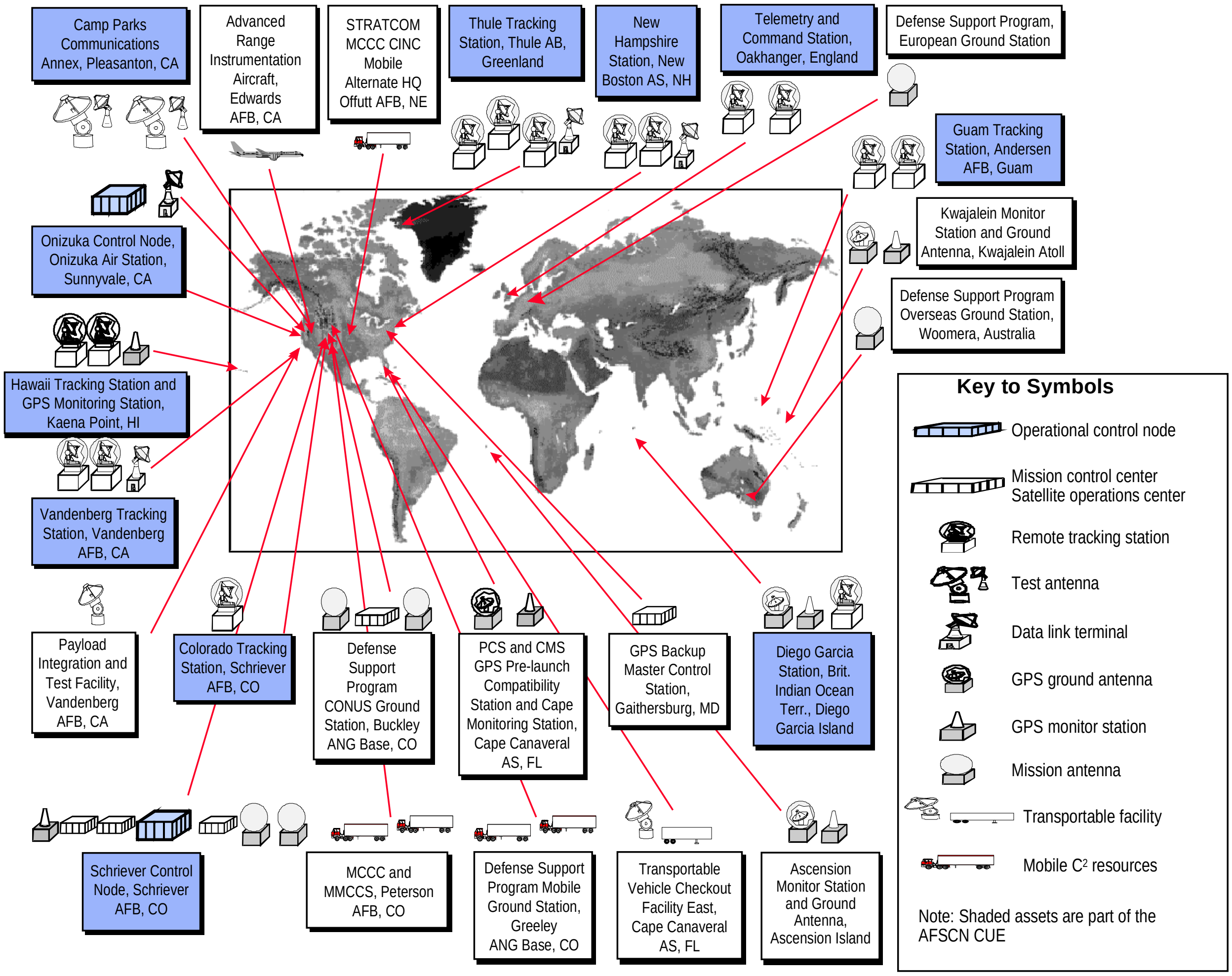
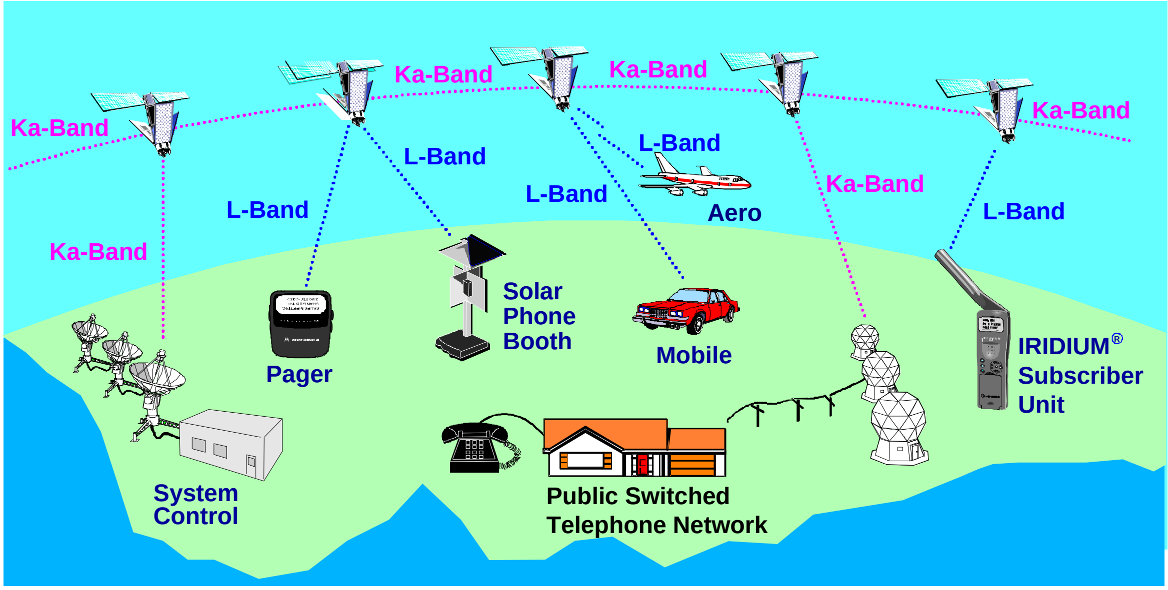


Figure I-2. *Air Force Satellite Control Network*



IRIDIUM is a registered trademark and service mark of Iridium LLC

Figure I-3. *Iridium Network*

The comparison of these principles and characteristics provides insight into the problems associated with the current military system of satellite operations and reveals some opportunities that are presented by commercial systems and practices. The following observations are intended to transcend the differences in missions and mission complexity of systems, in order to address broader principles that affect acquisition and operations.

- The problems of military satellite operations are complex and require more than an easy fix.
- The Air Force is trapped by an obsolete infrastructure, including systems that are costly to operate and maintain, and costly and difficult to upgrade.
- The technology incorporated in the Air Force systems is usually unique to each system (stovepiped), and much of it dates from the 1970s. This complicates maintenance and upgrades.
- The recapitalization plans for Air Force operating system upgrades are largely unfunded, extend over long periods, or don’t exist. This is also true for major capability upgrades—despite the existence of a number of programs addressing new capabilities in the Department of Defense (DoD). The rate of evolution in IT outpaces our Program Objective Memorandum (POM) budgeting process. Commercial industry is making business investment decisions on a much shorter time cycle to take advantage of the less-than-2-year IT cycle.
- The use of uniformed military personnel for routine system operations incurs costs and high error rates because of rotation, training, other duties, and a military personnel authorization and staffing system that is far less agile than its commercial counterpart.
- The very high reliability requirements placed on individual components drives costs significantly. Today’s commercial approach to system design is for individual components to have a lower reliability, hence a lower cost. The use of “spares” is also becoming normal commercial practice.
- The design approach that creates unique systems for each mission is a significant cost driver and raises barriers to standards-based evolution and commercial product incorporation.

2.3 Key Lessons Learned

The conversion to the use of and reliance on commercial systems is a significant change in the character of the operations and the basic culture of the Air Force. These kinds of changes have been recognized as necessary and have been carried out in some other large organizations. An example from the Boeing Company is given below.

The Boeing Company's Commercial Airplane Group was faced with a situation that is in some ways analogous to the situation with the Air Force's space assets—independent legacy systems controlling critical information. In Boeing's case, 450 independent legacy systems controlled the airplane definition, parts ordering, and shop floor planning of the 75 million parts required monthly to build airplanes.

A 5-year $1.5 billion activity to implement a new, integrated business information and management system was decided on to replace all the legacy systems. Almost all aspects of the new systems were put together from commercially available software. The system implementation was done in parallel with the existing systems, and the transition has been successfully completed.

Key Lessons Learned:

- The change must be driven from the top down
- No exceptions—every group will come up with reasons why they are different and can't implement the change
- Management, not the users, is the major inhibitor to change
- Consistency of purpose (and courage) is required to stay the course
- The need for education and training is consistently underestimated
- The cultural aspects of this change are far greater than the technical aspects

Cultural Change:

- Is like changing a tire at 60 miles per hour
- Is like open heart surgery during a marathon

"If you always do what you always did, you always get what you always got."

—VADM Tuttle

2.4 Recommendations

The dramatic increase of commercial capabilities, especially communication and imaging systems, offers opportunities for national defense systems in both capabilities and operational practices. In many areas, the Air Force is in a position to consume and use technology rather than create it.

The Air Force must begin to aggressively adopt and exploit commercial satellite operations technology, practices, and services. This is a paradigm shift for satellite operations—*use commercial first*, rather than using commercial as a supplement (see also Section 4.0).

Three specific recommendations will help in implementing this broad advice. The first two address wider system issues that would significantly reduce the infrastructure to support ground operations.

1. *The Air Force should get on board early with commercial space initiatives.* This will require participation in identifying the capabilities needed at the early stages of the development of these systems, and in some cases becoming an "anchor tenant" to have more leverage on the overall system characteristics. DoD participation in Iridium (albeit late in the cycle) is an excellent start to this process.
2. *The Air Force should use commercial infrastructure and satellite buses to support military payloads*. The Navy currently uses a commercial satellite bus for the Ultrahigh Frequency Follow-On (UFO) program, but retains satellite operations on government infrastructure. A comparison with Milstar, a more complex but generically similar military-unique system, shows that Milstar is almost 10 times more expensive (with a total common user cost of $2 million for UFO versus $18 million for Milstar). The Air Force should make maximum leverage of commercial satellite buses and their associated ground systems when procuring military payloads, and partition functionality to minimize the development of any ground-system elements needed for customized military-unique functions.
3. *The Air Force should use commercial operating practices to gain operational efficiency*. The Air Force should focus on improving the automation and user interface of existing satellite ground systems and set goals to significantly reduce staff. Proprietary obsolete workstations should be replaced with open-architecture commercial products and practices. Human factors professionals should be included at every stage of these improvements. Some planned control center upgrades at Air Force Space Command are a good start. The "military imperative" of staffing satellite ground systems with active duty personnel should be challenged and consideration given to converting many of these positions to Reserve/Guard, civil service, or contractor positions.

3.0 Mission-Centric Distributed Architecture

3.1 Introduction

Military operational effectiveness can be greatly improved by taking a mission-centric (or capability-centric) view across the enterprise. An aerospace force structure in which space, air, and terrestrial systems are integrated seamlessly and operate in a system-of-systems context offers an effective approach to exploiting the unique advantages of each medium. This beneficial integration transcends space, air, and ground to include various methods of intelligence, remote sensing, communications, navigation, and operational entities, stretching from sensor to shooter. Currently, space functions within the Air Force are stovepiped, not well integrated with air functions, and are often operated and tasked as independent and unique platforms. Likewise, within the intelligence community, technically sophisticated spaceborne sensors and ground facilities are dedicated to particular tasks in specified domains or regions of the electromagnetic spectrum. These systems are independently designed with little consideration of how cooperative and integrated tasking and collection could enhance overall utility.

This section of the panel's report strives to communicate the benefits and means for migrating from a platform-centric framework to an MCDA. The MCDA concept contains a layered functional model called a System-of-Systems Interconnect (SSI), which is similar to an Open Systems Interconnect (OSI).

An important element of this architecture is the use of emerging commercial systems and capabilities. In many cases the commercial marketplace has surpassed DoD technological and operational capabilities. Using a commercial approach to investment and recapitalization, commercial enterprises are able to accommodate via an SD process the rapid pace of change in the IT industry. Conversely, the military programming budget cycle for the waterfall development process does not favor new technology. Commercial practice and SD accommodate the 18-month technological innovation cycles while the classic POM approach works on a 6-year cycle. Commercial practices, products, and services are being developed and fielded with capability that exploits the space medium on a scale that dwarfs the efficiency of the classic Air Force approach.

Emerging space systems such as Iridium, Teledesic, and Spaceway could provide global communications coverage from space to space, space to ground, and air to space to air. Commercial Web-based tools being developed and fielded at a growing pace can provide the necessary communications and IT infrastructure. Combining the MCDA model with global commercial systems and capabilities essentially provides a virtual computing environment (VCE) in which any data or information can be processed at any location or platform with relevant information available to the right person at the right place at the right time. Utilization of the robust commercial space network combined with multiple air and terrestrial elements of a VCE also provides inherent survival advantages. To complete this functional information network, air-to-space communications must be improved. There is tremendous mission benefit, for example, in being able to cross-link air resource information—such as the Joint Surveillance, Target, and Attack Radar System (JointSTARS)—to space as the gateway to the battlefield.

3.2 Benefits of Mission-Centric Architecture

Current systems are structured around the platform the system uses. The infrastructure, management, and hardware for current intelligence, surveillance, and reconnaissance (ISR) systems evolve around the individual platform or medium. Growth for each function within the system has been constrained to coincide with the evolution of the system as a whole. These platform-centric solutions have produced systems with unique infrastructure designs. Platform-centric solutions are expensive to develop and maintain, and difficult to integrate across platforms.

Inherent in the MCDA is a communications backbone allowing for distribution of the functions needed to perform a mission from a mission-centric perspective. Thus the functions can evolve separately within the system with improved mission effectiveness and efficiency.

In the following sections we describe some of the candidate missions that would benefit from a mission-centric architecture.

3.2.1 Suppression of Enemy Air Defenses (SEAD)

The goal of SEAD is to make enemy air defenses as ineffective as possible. That means destroying the defense or causing it to be off the air during the times the United States is in the air. Signals intelligence (SIGINT) assets are tasked against active defense emitters, ground moving-target indicator (GMTI) systems are tasked to track out-of-garrison movements, and imagery intelligence (IMINT) systems are tasked to provide targeting-level information with real-time information interchange with SIGINT and GMTI systems for queuing and information fusion. Next, the SEAD mission execution uses aerospace C^2 assets to direct an aircraft or missile to eliminate the targeted surface-to-air missile (SAM) system. Finally, an ISR asset is required for a battle damage assessment (BDA) to determine mission success. This scenario is shown in Figure I-4.

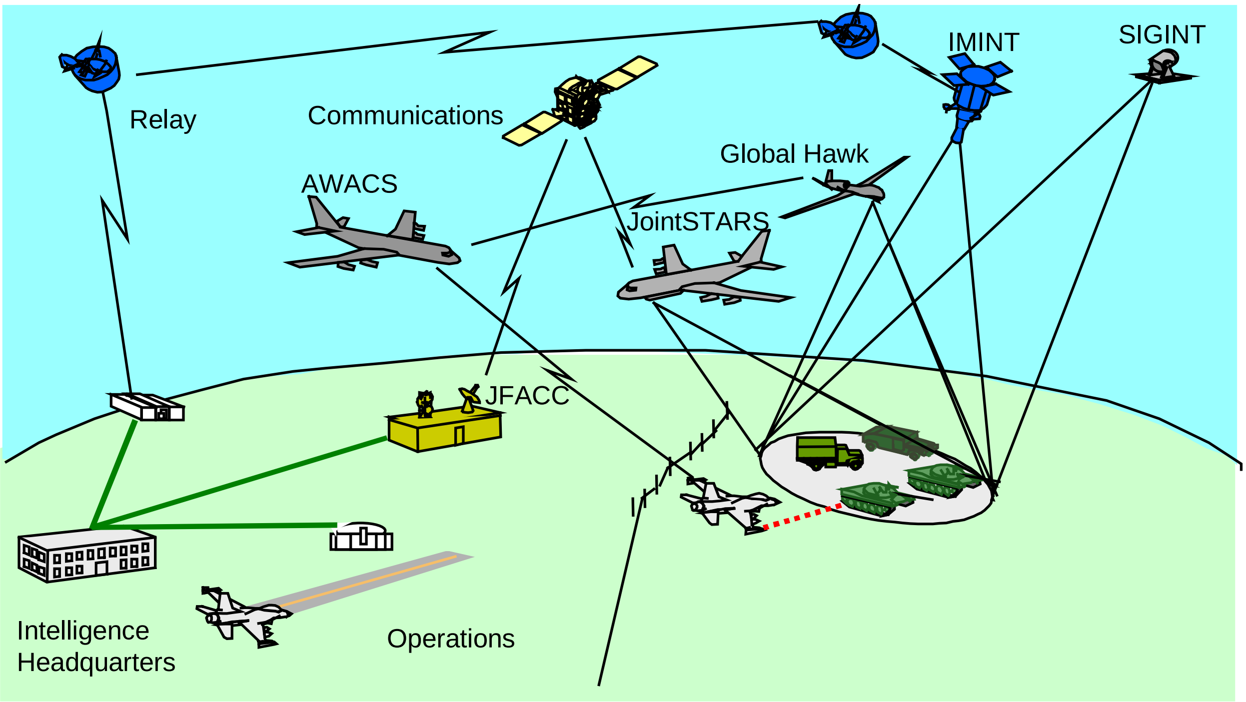


Figure I-4. *Suppression of Enemy Air Defenses*

Coordination of this type of mission in the current platform-centric architecture requires a large staff and widely varied expertise from many locations and is inherently difficult. Moving to an MCDA will improve our overall mission effectiveness.

3.2.2 Global Air Navigation Systems (GANS)

The GANS study performed by the SAB[3] examined the needs and possibilities for navigation systems to be used by the Air Force of the 21st century. Changes in the global civil airspace architecture and global air traffic management (GATM) procedures will necessitate changes in Air Force equipment and procedures to maintain rapid, unrestricted global access by DoD aircraft. The DoD operates approximately 15,000 aircraft, all of which will be affected by changes in the airspace architecture over the next 15 years. Cost estimates vary depending on the options implemented, but the cost could approach $15 billion if traditional equipage approaches are used.

The GANS study recommended that the Air Force take a proactive role to lead the development of future international airspace architectures.[4] There is growing acceptance in the international aviation community of establishing performance criteria rather than mandating aircraft and Air Traffic Control (ATC) equipment. The acceptance of military systems that meet the Required Navigation Performance and Required Communication Performance standards for civil aviation certification has the potential to significantly reduce the costs that will be incurred by the Air Force to achieve the goal of rapid, unrestricted global access. The adoption of Global Positioning System (GPS) data, reported to the ATC on command, will also enable Air Force aircraft to be compliant with autonomous dependent surveillance (ADS) requirements. The Air Force is uniquely positioned to take advantage of new capabilities in mobile and networked communications to meet ATC requirements, since the DoD is a certifying agency with

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[3] U.S. Air Force Scientific Advisory Board study, Global Air Navigation Systems, Summary Volume, 1996.
[4] Ibid.

authority equal to that of the Federal Aviation Administration and is also an operator of an ATC system that interfaces with civil ATC functions.

Communications and surveillance recommendations from the GANS study included adopting a network approach to enable the Air Force ATC system to act as a gateway between military datalinks and civil ATC. By adopting this network architecture, existing (and planned) military capabilities can be leveraged on Air Force aircraft that have capabilities far beyond those needed for civil GATM. Installing the military datalink interfaces (gateways) with the ATC organizations will be less expensive than installing additional equipment in all DoD aircraft. These ATC network communications and gateway facilities can also become part of the DoD new worldwide C^2 system, which will make ATC information immediately available for mission planning and inclusion as part of a global awareness function.

The GANS study also concluded that collaboration with commercial satellite communications (SATCOM) suppliers to ensure low-cost, reliable aviation services with military capability would enhance the Air Force capability to meet future GATM and C^2 needs. A SATCOM system linked to GPS with data and voice connectivity to ATC facilities illustrates the benefits of a functionally distributed architecture. The GPS and SATCOM datalink provides the ADS functionality, which obviates radar surveillance for ATC functions. The network link through SATCOM provides connectivity to both the C^2 network for warfighting functions and the Air Force ATC gateway for civil ATC communications.

If the Air Force adopts the mission-centric approach proposed by the GANS study, and distributes functionality to the network architecture through GPS and mobile communication links, the capability of each aircraft platform can be increased. This migration from a platform-centric viewpoint, in which each aircraft is upgraded to meet global aviation requirements, to an MCDA leveraging air and space distributed functional components can save significant costs.

3.2.3 Interlinked Imagery Management

In our current platform-centric architecture, the imagery process (requirements, tasking, exploitation, dissemination, and archiving and retrieval) is managed independently for national, tactical (Predator, U-2, etc.), and commercial (SPOT, Landsat, RADARSAT, etc.) systems. Future government systems, Discoverer II, new national systems, unmanned aerial vehicles (UAVs), and the explosion in commercial systems offer a significant potential for military use that warrants efficient management.

Linking the national, tactical, and commercial management information systems for imagery requirement would enhance overall efficiency. Integrated information access and standard “warrior” interfaces would increase military effectiveness. Missions supported include classic intelligence and operations (J-2, J-3); order of battle; science and technology (S&T); indication and warning; mapping, charting, and geodesy; intelligence preparation of the battlefield; BDA; special operations support; campaign planning; and battle and engagement execution.

Web-based technology and distributed information management approaches are available to integrate existing platform-centric systems. This technology includes search engines similar to Yahoo!™, commercial and government standards-based information exchange systems such as “True Video on Demand,” global broadcast, national imagery transmission format, information transfer protocol, and metadata concepts. A spiral evolutionary approach to linking the requirements management processes should be initiated now. The initiative should transcend the classic J-2/J-3 interface. For example, the National Imagery and Mapping Agency’s (NIMA’s) Requirement Management System and NIMA libraries programs should be interlinked with the U-2, Predator, and Eagle Vision II systems. This would offer efficiencies and operational utility improvements by linking national, tactical, and commercial capability in meeting imagery requirements. Initiatives such as Battlefield Awareness and Data Dissemination (BADD) and Dynamic Data Base address both technical and operational concepts associated with the integration challenges.

3.3 Notional System-of-Systems Interconnect Model

Defining a mission-centric architecture in terms of the current platform-centric architecture is difficult because of the seemingly disparate set of functions employed across air, space, and ground systems. Before specifying changes or additions to the Air Force's physical architecture, it is necessary to develop a functional architecture that can be universally applied to air, space, and ground missions. The SSI model is purposely kept simple. It is functional, not physical, and assumes that connectivity is transparent to the functional layers. By applying the SSI model to functional tasks currently distributed across air, space, and ground systems, the Air Force can identify areas of overlap, inefficiencies, and omissions.

3.3.1 SSI Tasks

Regardless of the action—analyzing intelligence data collected by a National Reconnaissance Office (NRO) satellite, vectoring fighters against hostile aircraft in a defense counter-air mission, or targeting and killing a SAM site by an F-16 pilot—six general tasks are performed within each system, as shown in Figure I-5.

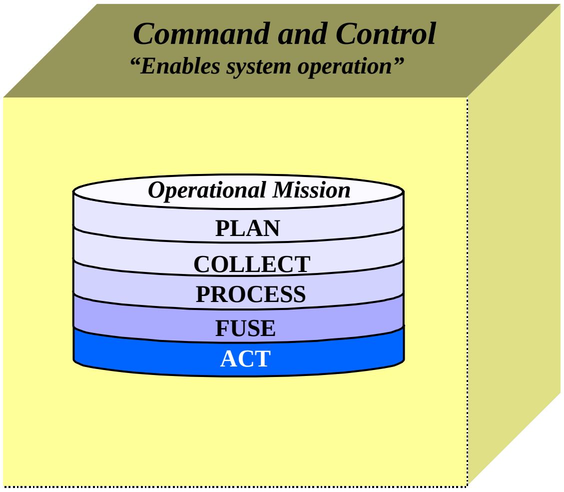


Figure I-5. *Generalized SSI Model*

- Plan. Planning takes top-down, directed tasking from the national C^2 hierarchy as input and develops the execution plan for this particular mission or system. The fundamental purpose of the plan task is to allocate finite resources (such as fuel for aircraft, or satellite power and access time for on-orbit systems) against the tasking requirements for execution.

- Collect. Most systems in today's physical architecture collect data or information from sensors, other systems, or organizations to conduct operations. The collect function encompasses those tasks necessary for obtaining the required information for the system. The data collected are typically raw and require additional processing for mission use.

- Process. The process function includes all processes needed to transform collected raw data into usable mission data—for example, the processing embedded in a sensor system to transform raw radar threshold crossings into detected target reports; processing to turn collected pulse descriptor words from an electronic intelligence (ELINT) collector into emitter line, bearing, and ID; and processing in an intelligence ground station to produce a finished intelligence product.

- Fuse. Fusing collects multiple data sets from the processing task of one or more systems and processes those data into information relevant to mission operations. This function could include processing pulse descriptor words from multiple platforms to establish a single target ellipse using time-difference-of-arrival techniques, or multiple sensor target reports to establish a target track with ID. The fusing function is key to mission operation because it takes data as input and delivers operationally useful information or knowledge as its output.

- Act. Information created from the fuse function is useless unless someone acts on it. The act function recognizes that data turned into information are collected for an ultimate purpose, defined by the initial tasking input to the plan function. Actions could include archiving information into an ever-growing database, committing fighter aircraft to engage an enemy aircraft in air-to-air combat, or a pilot's decision to fire a missile.

- Command and Control. C^2 within this system model refers to those tasks necessary for successful operation—for instance, monitoring health and status and maintaining system readiness and availability. These functions cut across the other five functions in the model and actually work in the background to guarantee mission success.

3.3.2 SSI Model Application to Existing Missions

An illustration of the generalized nature of the SSI model is provided in Table I-2. The model is applied to four different mission areas at every level of the command hierarchy: campaign planning, intelligence collection management, battle management/command, control, communication, computers, and intelligence (C^4I), and fighter engagement.

Table I-2. *Application of the Generalized SSI Model*

	Campaign Planning	***Intelligence Collection Management***	***Battle Management C^4I (BMC^4I)***	***Fighter Engagement***
Plan	Input: Joint Forces Air Component Commander (JFACC) Strategy to task, plan tasks	Input: Collection requirements Satellite mission planning	Input: Air tasking order (ATO) Aircraft mission planning (orbits, waypoints, and communications plan)	Input: ATO Aircraft mission planning (waypoints, communications plan, weapons, and fusing)
Collect	Compile intelligence, base resources (aircraft, weapons), *Joint Munitions Effectiveness Manual*	Payload upload, operations, downlink	Sensor configuration, collect raw sensor returns, Xtold data	Sensor configuration, collect raw sensor returns, Xtold data
Process	Build intelligence, prepare battlespace, develop target list, determine aircraft readiness, logistics support	Intelligence product formation	Create target reports, filter Xtold data	Create target reports, display Xtold
Fuse	Deconflict, assign assets to tasks/targets	Exploitation, decision aids, correlation	Fuse/associate, track, combat ID	Fuse/associate, track, combat ID, target
Act	Correlate to strategy to task to technology, approve and disseminate ATO	Disseminate intelligence products	Conduct battle assessment, commit fighters, disseminate tracks, control	Confirm ID, shoot, evade, conduct countermeasures
C^2	Air Operations Center system administration	Monitor telemetry, tracking, and control	On-board systems technology, monitor status and health	Pilot-initiated engagements, externally initiated engagements
Time Required	**Approximately 24 hours**	**10 minutes to 5 hours**	**5 seconds to 5 minutes**	**Less than 3 seconds**

Each of these applications can be modeled with the SSI construct, but the timeliness and quality requirements for each mission application are very different. The fighter pilot goes through the same six functions in targeting and killing an enemy fighter as the Joint Forces Air Component Commander (JFACC) and the Commander's staff do in planning the campaign, but the quality and timeliness of the information required is much different. It is imperative that any physical architecture that implements the functional architecture meet the varying range of quality required across the command hierarchy.

As illustrated in Table I-2, the SSI model is often implemented sequentially from plan to act. As the Air Force moves to a mission-centric architecture, the SSI model must allow for the distribution of functions in time and space as well as entry and feedback to or from any function. These features are consistent with the AEF employment concepts of smaller forward footprint, en route/dynamic mission planning, and a virtual air operations center (AOC) operating within the continental United States.

The limitations of the Air Force's current employment of this functional architecture can be demonstrated through a simple example: a pop-up mobile SAM site. Figure I-6 shows the hierarchy from campaign planning to intelligence support to battle management to weapon engagement:

1. The air tasking order (ATO) is generated at the AOC with the JFACC's strategy-to-task analysis as input. The ATO assigns specific assets to the daily mission.

2. The intelligence cell of the AOC coordinates overhead collection against possible SAM sites with the Overhead Collection Management Center (OCMC). The OCMC forwards the approved tasking order to the appropriate operations directorate for execution.
3. The overhead collector detects a SAM in theater and reports this information via intelligence broadcast channels to Rivet Joint flying in theater.
4. Rivet Joint configures its system to look for the SAM. Rivet Joint receives an accurate line, bearing, and ID of a mobile SAM site and disseminates the information via the Joint Tactical Information Distribution System (JTIDS).
5. When JointSTARS sees the SAM location from Rivet Joint, it begins monitoring movement from the area of the SAM site.
6. The Airborne Warning and Control System (AWACS) updates its situational awareness as a result of the detected SAM location.
7. AWACS operators direct F-16s and F-15Cs under their control to avoid the known SAM site.
8. AWACS commits loitering F-15Es to the SAM site.
9. As the F-15Es are en route, JointSTARS detects movement from the region of interest and passes the ground tracks via JTIDS.
10. AWACS redirects the F-15Es to the new location of the mobile SAM.
11. The F-15Es detect, target, and fire upon the mobile SAM transporter-erector-launchers.
12. Mission execution is passed to the AOC via voice communications. The intelligence cell of the AOC requests IMINT collection of the target area for BDA, which is allocated via tasking order to a U-2 asset.
13. The U-2 Wing Operations Center replans the U-2 trajectory and sensor collection parameters to collect against the target area.
14. Imagery collected by the U-2 is analyzed and target destruction is confirmed.

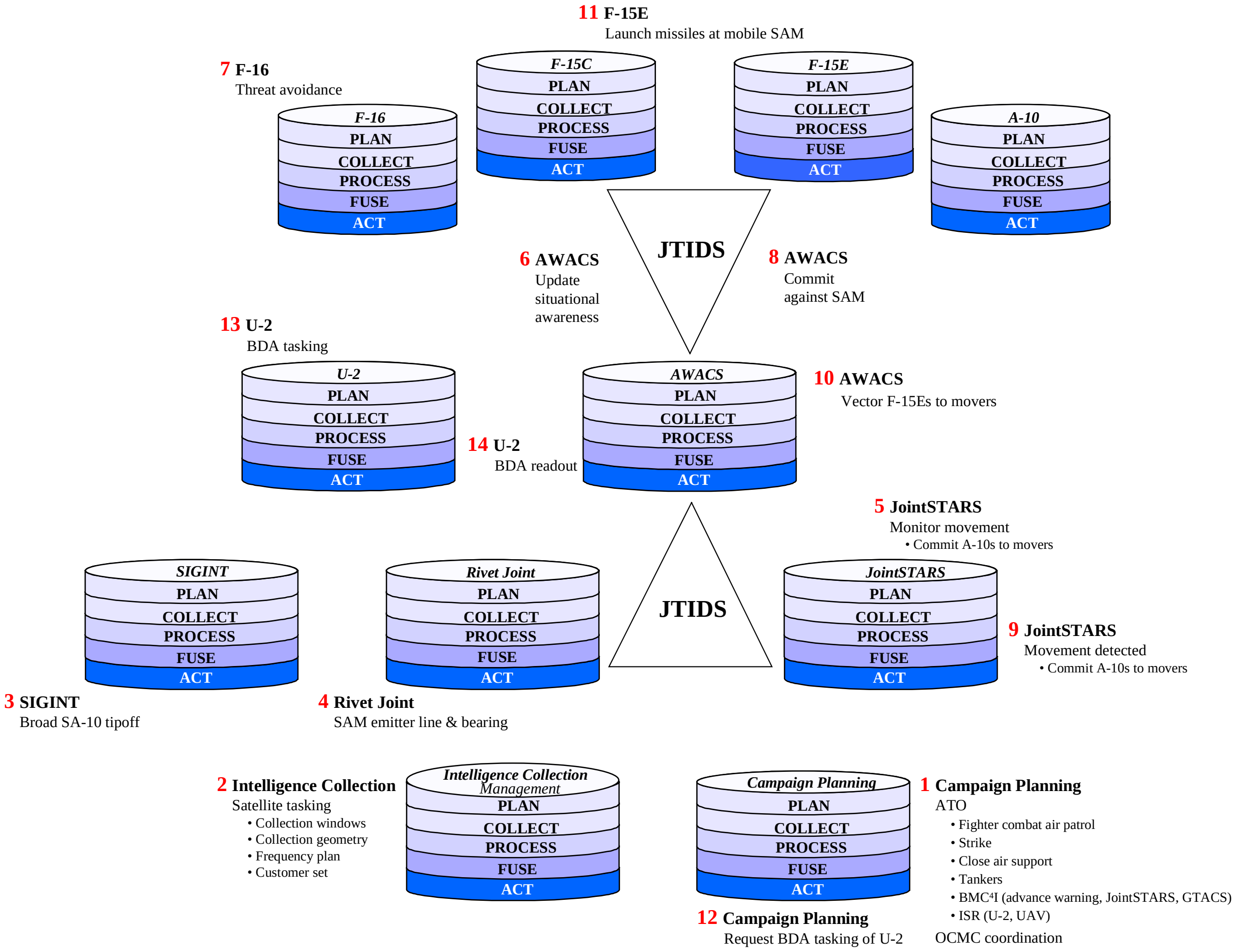
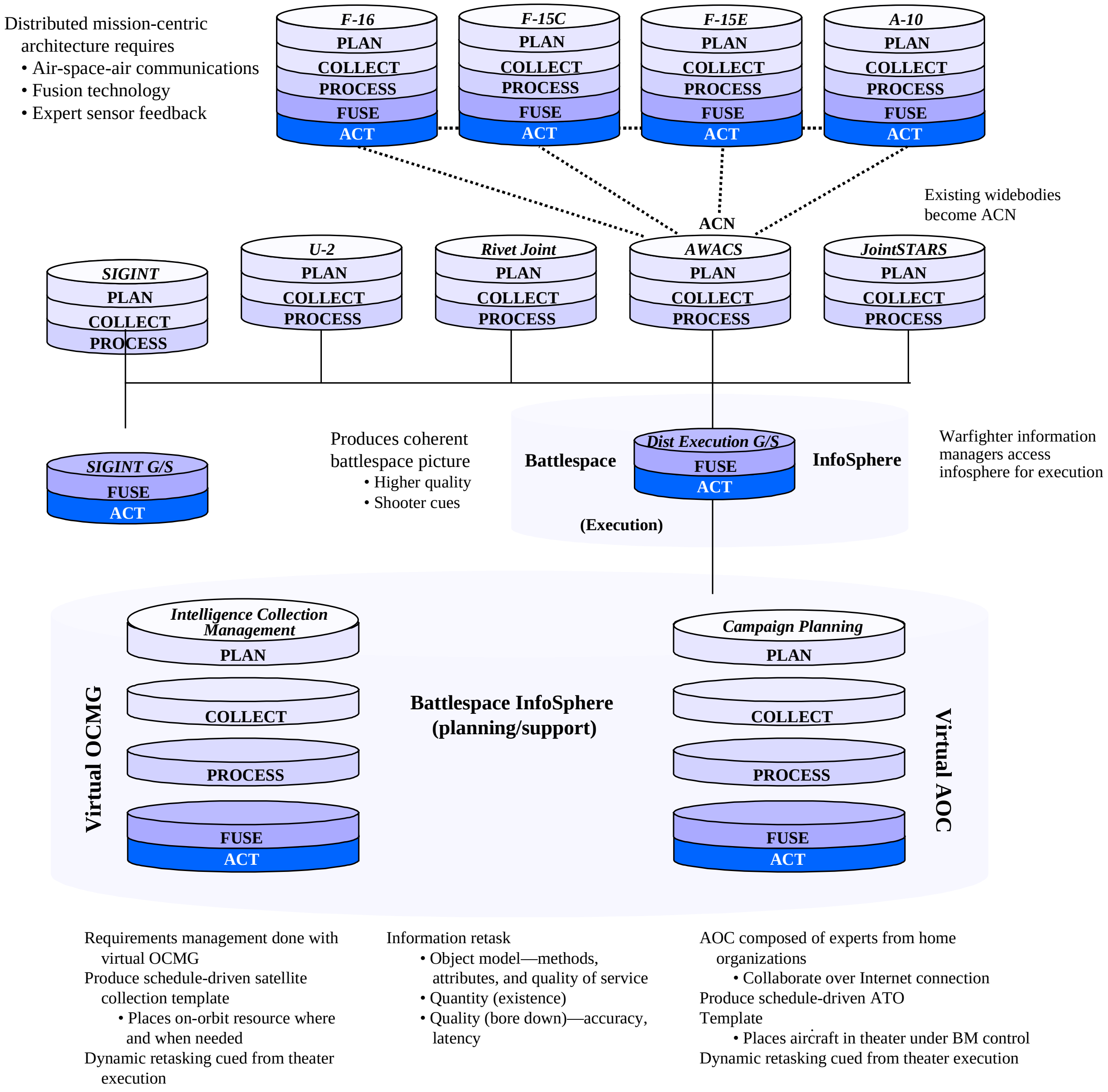


Figure I-6. *Warfighter Execution Example: Pop-Up SAM*

This simple example shows that today's stovepipe air-space-ground architecture requires a large staff and relies heavily on voice communication and some datalink communication. Several functions performed throughout the example are redundant across tactical assets (fusing and acting for AWACS, JointSTARS, and Rivet Joint). Also, there is very little automated interaction between the AOC planning functions and the intelligence community's collection management process.

3.3.3 SSI Model Application to a Mission-Centric Distributed Architecture

An MCDA leads to an efficient allocation of functions across the different mission areas. Figure I-7 shows a notional implementation of the SSI model to an MCDA. Both the AOC and the intelligence collection management function can be accomplished in a distributed fashion with experts coordinating and collaborating on the plans via Internet white boards and collaborative tools. Each of these planning entities draws from the planning and support Battlespace InfoSphere of distributed data and processes required for each set of tasks. The same functions are performed as in Figure I-6, but not necessarily in the same location. This approach significantly reduces the amount of forward-deployed personnel for a forward air operations center. The Defense Advanced Research Projects Agency's (DARPA's) JFACC-after-next and the AEF experiment will develop and evaluate operational concepts to implement this virtual planning environment.



Distributed mission-centric architecture requires
- Air-space-air communications
- Fusion technology
- Expert sensor feedback

Existing widebodies become ACN

Produces coherent battlespace picture
- Higher quality
- Shooter cues

Warfighter information managers access infosphere for execution

Requirements management done with virtual OCMG

Produce schedule-driven satellite collection template
- Places on-orbit resource where and when needed

Dynamic retasking cued from theater execution

Information retask
- Object model—methods, attributes, and quality of service
- Quantity (existence)
- Quality (bore down)—accuracy, latency

AOC composed of experts from home organizations
- Collaborate over Internet connection

Produce schedule-driven ATO Template
- Places aircraft in theater under BM control

Dynamic retasking cued from theater execution

Figure I-7. *SSI Model Applied to Mission-Centric Distributed Architecture*

The *fuse* and *act* functions formerly residing with each of their respective platforms are now performed once on data collected from AWACS, JointSTARS, Rivet Joint, tactical reconnaissance (U-2), and overhead sensors. The benefit of a single fusion function for relevant information is evident. In Figure I-6, the data collected by each of the sensor platforms were processed and fused before being disseminated to the other platforms in the theater. When the raw processed sensor data are fused (or filtered) only once, as in Figure I-7, the quality of the result improves. Furthermore, the interaction between AWACS, JointSTARS, and Rivet Joint previously accomplished via JTIDS and voice communications can be performed by battle managers residing in the same physical location looking at the same coherent battlespace picture—a more timely and accurate picture than the common operational picture generated by the AOC’s planning applications. The battle managers residing at the Distributed Execution Ground Station become information managers. Their purpose is twofold: first, to manage the transformation of the data coming into their function into operationally useful information; and second, to perform the battle management functions of controlling theater aerospace assets in the execution of the combat plan.

As the battle managers are moved from the airborne widebodies to the Distributed Execution Ground Station, space and power become available to add sensors or a communications switch, making the tactical heavies airborne communication nodes (ACNs) for the disadvantaged users in theater, such as fighters and Army ground units. The information managers operating on the Battlespace InfoSphere for Execution require automated feedback to the infosphere for increased quality of service (QoS) on the objects in the infosphere. For instance, if the information manager needs 1-minute updates on moving-target indicator data for fast-moving targets under surveillance, the manager can request the QoS on the target object; the Battlespace InfoSphere processes will automatically convert the QoS request to system tasking. The tasking is accomplished and the data transmitted into the infosphere for execution, providing the information manager with the quality of data required.

3.4 Illustrative MCDA Implementation

Figure I-8 illustrates the advantages of a mission-centric and network-centric architecture as applied to a Space-Based Infrared System (SBIRS)/Joint Tactical Ground Station (JTAGS) mission. Today, platform-centric planning functions are typically collocated with C^2 as well as processing/fusion and user functions. For this reason, the military often desires direct downlink to theater, whereby mission-collected data can be processed and assessed against a different set of criteria. In our future vision with the mission-centric and network-centric architecture, global communication networks are available to distribute the appropriate information to the appropriate location or personnel. Where planning, C^2, processing/fusion, and decision making physically reside then becomes academic. The functions listed below are accomplished with respect to the steps shown in Figure I-8:

- Steps 1–2: Planning and tasking output are relayed to C^2
- Step 3: C^2 commands are uplinked to three satellites
- Step 4: “Sensor head” satellites pass information to the “processing head” satellite
- Steps 5–7: Mission-collected data are downlinked through a space-based commercial network to the fusion center
- Steps 8–11: Processed and fused information is disseminated to aircraft and ground personnel
- Steps 12–13: Retasking allows for real-time or adaptive changes to be forwarded (relayed) to C^2 on the basis of observables
- Step 14: C^2 modifications are transmitted to satellites according to assessment and retasking

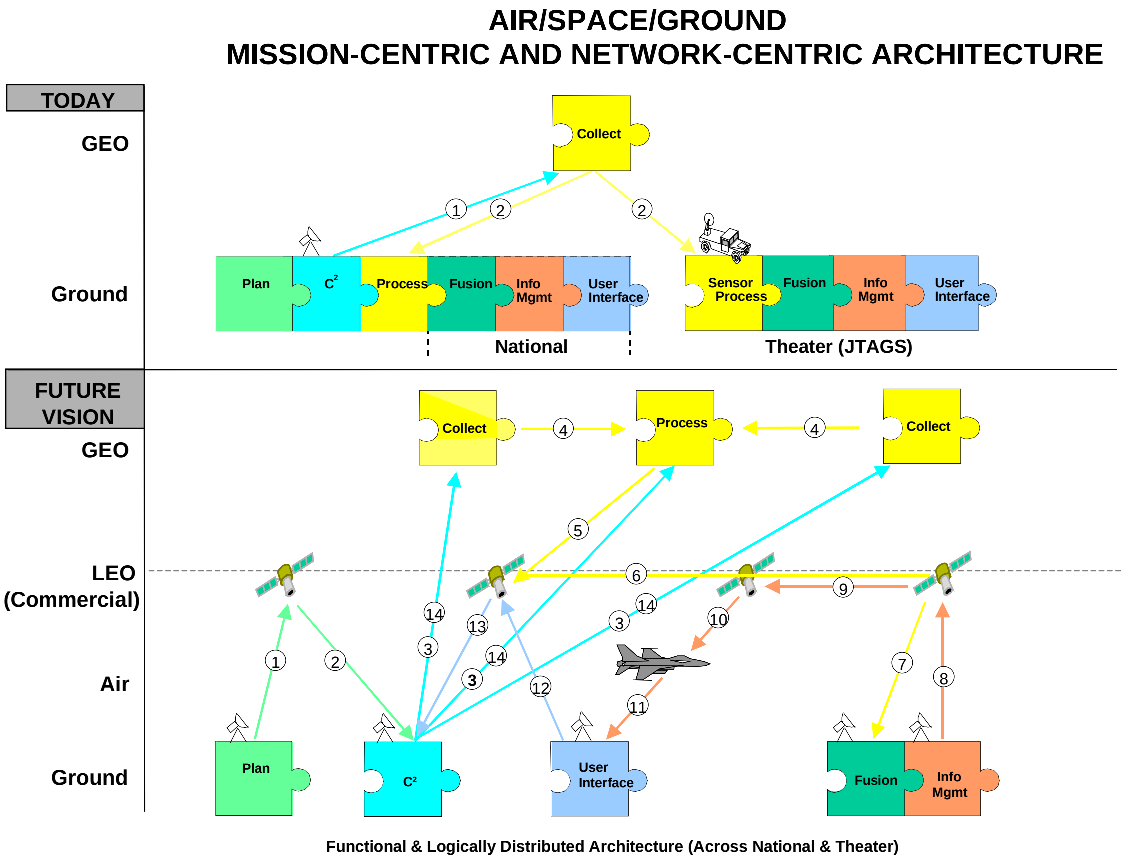


Figure I-8. *SBIRS/JTAGS Network-Centric Model*

The mission-centric and network-centric approach has the following advantages:

- Personnel and expertise that can be distributed where and when needed regionally but ganged together for critical mass and surge (collaborative virtual workspace)
- Scarce resource personnel expertise that can be centralized while capability (photo interpreters, language interpreters, battle managers) are distributing
- Lower-cost replenishment options after in-orbit failures
- Flexibility for separate sensor heads and processing heads
- Improved aircraft information dissemination (space direct downlink to air)
- Flexibility in transitioning the pieces (for example, frequency band differences)
- National and theater assets and resources that can be integrated

3.5 Evolving Programs and Technology

A number of current and evolving DoD programs have begun activities that we believe fit the objectives of this transition. Examples include BADD, a distributed JFACC, the Virtual Hub, Eagle Vision, and the Expeditionary Force Experiment (EFX).

- The BADD Advanced Concept Technology Demonstration (ACTD; see Figure I-9) addresses distributed repositories and mission-centric dissemination. Although it is not obvious that the demonstration has incorporated integrated tasking, it nonetheless serves as an excellent model for both mission-centric and network-centric operational concepts across national, military, and commercial assets. The BADD ACTD may provide a good environment for expansion into the broader scope of mission-centric planning and tasking.
- The JFACC-after-next (see Figure I-10) adds mission-related, distributed, event-driven flexibility and retasking. It is also an excellent example of both mission-centric and network-centric concepts.
- The NRO "Virtual Hub" uses commercial Web-based tools to provide information management and communications middleware services that functionally reside between the information repositories and the user.
- Eagle Vision combines integrated source imagery and exploitation across intelligence and commercial entities.
- EFX demonstrates the validity of network-centric concepts relative to the AEF mission.

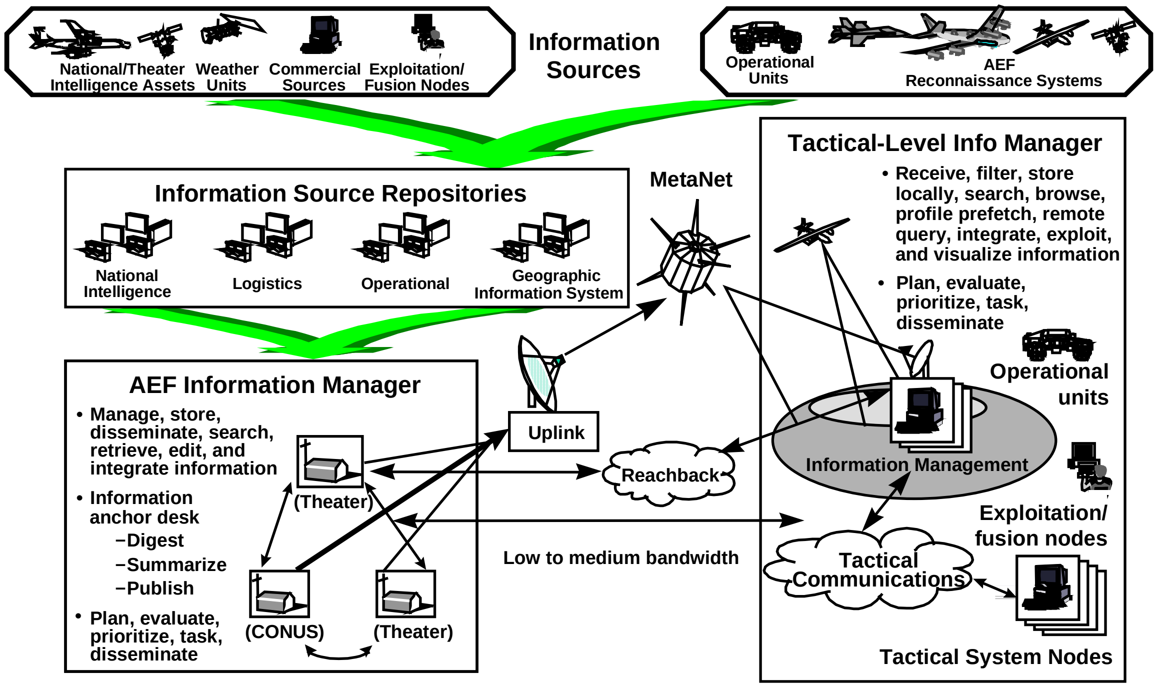


Figure I-9. *Battlefield Awareness and Data Dissemination*

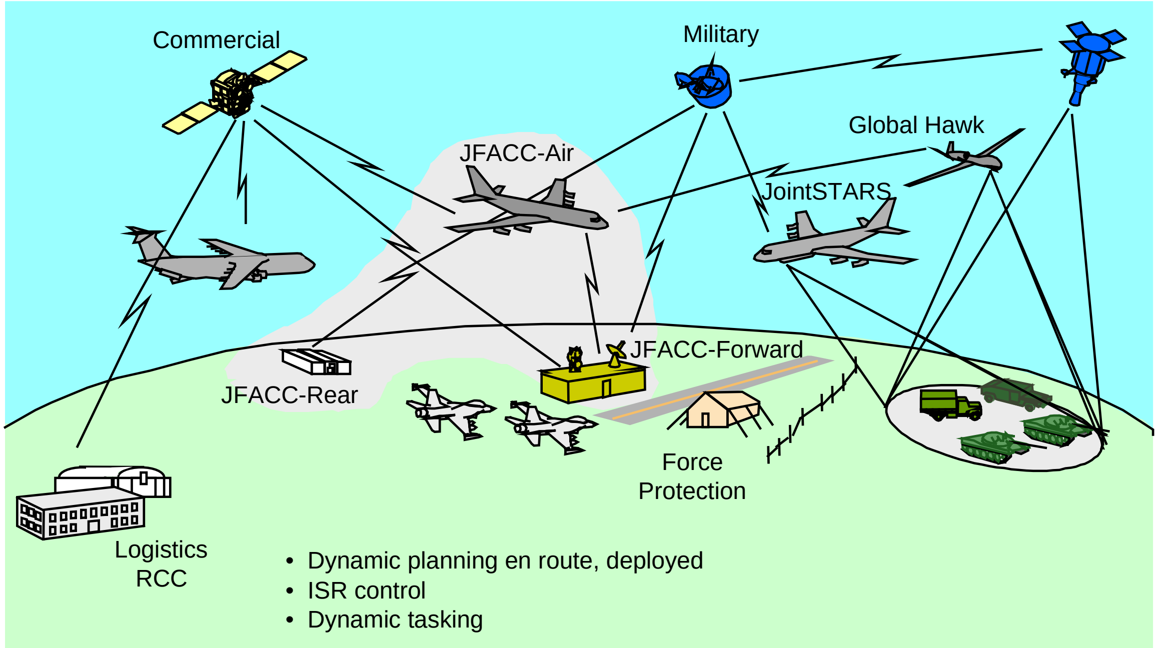


Figure I-10. *JFACC-After-Next*

Information management-related technology enablers that are required for the Battlespace InfoSphere architecture are addressed by the 1998 SAB Ad Hoc Information Management and Technology Panel[5] and are consistent with the MCDA requirements.

3.6 Rethinking Organizational Roles

Adopting a mission focus vice a platform focus involves rethinking organizational and functional roles. For example, the Air Force interaction and planning process takes a “program” view. Program elements are used in the programming process. In a mission-centric view, program elements could be aggregated into a mission element. Other organizational and even doctrinal issues arise when we take a mission view. The classic J-2/J-3 roles are blurred when we think of the infosphere and its relationship to a mission. In today’s structure we have significant distinctions between intelligence data (for example, ELINT geolocation) and operational information (for example, JointSTARS). To the infosphere and to the ultimate warfighter, knowledge is what is important. While it is recognized that intelligence means and methods are important, our security systems are very capable of protecting what warrants protection. Infosphere information access should be privilege-controlled (by system administration) instead of organizational. Systems such as Radiant Mercury™ facilitate automated, rule-based, intelligence-derived information handling.

Another organizational example of platform versus mission orientation is evident in the Air Force acquisition organizational structure. Projects are often assigned to development centers on the basis of platform vice mission. Should GMTI from space (Discover II) be a Space and Missile Systems Center (SMC) program, or would it be better managed in association with JointSTARS? What we seem to be fostering is a platform competition between air (manned and unmanned) and space platform advocates when the mission is GMTI. The panel was pleased to note the leadership initiative between the directors of SMC and Electronic Systems Center (ESC) to address technological and mission synergy.

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[5] Information Management and Technology.

A mission-centric approach to aerospace integration fosters a doctrine that distributes mission functions to air, space, and terrestrial elements. Mission-centric aerospace integration spans the programming, budgeting, development, and operation functions. The mission is aerospace focused, not air versus space versus terrestrial.

3.7 Recommendations

Three top-level summary recommendations are provided here to transform the objectives of this chapter into reality:

1. *Migrate from a platform-centric architecture to MCDA to improve overall mission effectiveness*. In order to meet the objectives of the 2010/2020 long-range plan, DoD must expand beyond global communications and network management into global information management. We suggest that the Air Force initiate a mission-centric distributed architecture study based upon the above recommendations. The study should provide a more detailed system description than what can be accomplished during this short SAB study period and contain concept of operations (CONOPS), organizational implication, life-cycle cost/benefit, and Measures of Effectiveness metrics. The collaborative Web-like environment and virtual compute environment that enable distributed mission operations should be addressed within the study in conjunction with the Battlespace InfoSphere concepts.
2. *Migrate to a network-centric space-based communications structure to enable the global connectivity required for integrated aerospace missions*. Global space-based communications, air-to-space communications, and information management technology enhancements are key to enabling the mission-centric vision. Global space-based commercial communications will rapidly develop with or without participation from DoD. Since the commercially available capacity will dwarf the DoD capacity, DoD needs to partner with industry in these early developmental stages in order to ensure overall viability. Investment is recommended in developing air-space-air communications to enable all future U.S. Air Force aircraft to be connected into the spaceborne internet architecture.
3. *Establish a collaborative Web-like environment, compatible with the Battlespace InfoSphere architecture, to enable distributed mission operations*. Information management tools, such as those recommended by the SAB's Ad Hoc Panel on Information Management and Technology, are needed to leverage a distributed mission-centric architecture that can fuse data across sensor modalities, time, and space. Expert QoS tasking techniques are also needed for converting QoS requests to system-of-systems tasking to best utilize the optimum asset (whether military, commercial, air, space, manned, or unmanned) to achieve a mission's objective.

4.0 Connectivity for the Network-Centric Battlespace

4.1 Introduction

The MCDA implementation shown in Figure I-7 requires three key technologies:

- Air-space-air communications into the spaceborne Internet architecture so that sensor data can be transmitted from the theater to the Distributed Execution Ground Station.
- Information management tools to include data fusion engines that can fuse data across sensor modalities, time, and space. These tools are the subject of the SAB's Ad Hoc Panel on Information Management and Technology.

- Expert QoS tasking techniques for coverting QoS requests to system-of-systems tasking.

It is somewhat ironic that in order to achieve tight interaction and collaboration between all levels of the command structure and platforms making up the system of systems, the physical architecture must become a loosely coupled, distributed computing environment.

The implementation of a functionally distributed architecture depends on access to a network-centric communication architecture to tie together the air, space, and ground elements.

In our vision of the future, this information network (the infostructure) will enable more efficient and cost-effective operations by providing the following capabilities:

- Network connectivity between the different functional elements needed to support a mission (for example, tasking, C^2, sensors, and information management)
- Distribution of data and information across a battlespace network without being tied to direct links from sensors to users
- Information distribution with maximum leverage of existing emerging infrastructure, C^2 functions, and communication links
- Improved operations for existing ground and air systems by providing networked access to an extended infosphere
- Integration of space (military and civil) and air (manned and unmanned) platforms into mission-centric operations (that is, accessing best resources to achieve a specific end)

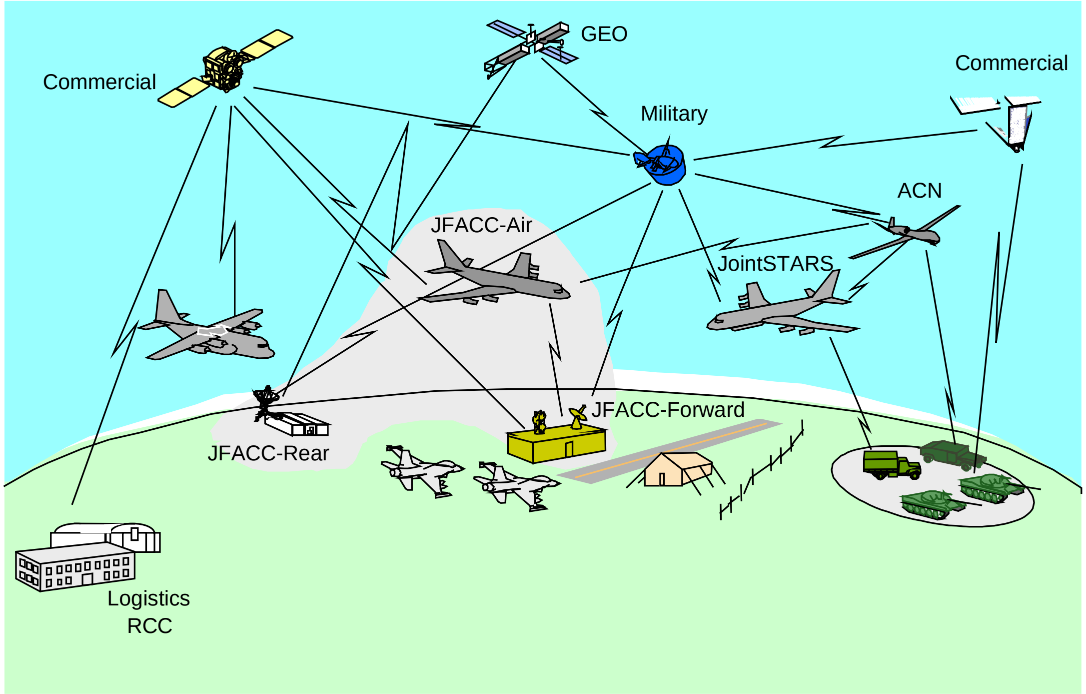

Figure I-11. *Network-Centric Battlespace*

To enable this vision, robust reliable communications are needed to support connectivity among the different tasking and information nodes on the network. As illustrated in Figure I-11, this will require integration among a variety of military and commercial communication networks. We envision this infostructure as relying heavily on commercial communications to provide space-ground-space network connectivity and also to provide space-space connectivity and air-space-air connectivity to tie military space and airborne platforms into the global grid. Our vision also includes cross-network integration in which nodes on the network can provide a bridge between the commercial communications link and legacy DoD systems operating with military communication links. For example, global connectivity to any common ground station (CGS) could be provided by upgrading JointSTARS with a SATCOM datalink to create a bridge to the Surveillance Control Data Link used to communicate with the CGS ground station. Through effective use of bridges between commercial and military communication services, a robust, reliable, redundant network architecture can evolve based on progressive upgrades to existing legacy systems and infrastructure.

4.2 Communication Systems

In Section 3.0, we introduce the concept of an SSI model, which describes the functionally distributed components required to implement a specific mission. Interconnecting these components requires a network architecture, which can also be described using the OSI model. (Figure I-8 illustrates the relationship between the SSI and OSI models for SBIRS/JTAGS.)

To implement the battlespace network, the architecture must address all of the layers (application to physical) of the OSI model. Challenges are faced in each of these layers. The Information Management Ad Hoc study addresses many of the issues associated with the higher layers of operating the battlespace network.[6] A management function is needed that can implement the network layers of this model to enable all functional elements to be accessed with a user-unique address. Since many disparate physical links and protocols may be used in the total battlespace network, a network management system is needed to enable universal user addresses that are independent of the individual communication systems. By using gateways and bridges between the many heterogeneous communication systems in use by the military, a robust web can be implemented using redundant paths to maximize delivery of communications to the user. Gateways and bridges also enable legacy systems to gain access to new capabilities without the penalty of upgrade or replacement costs for user equipment.

The following sections address the physical layer of the battlespace network and some of the existing and future commercial and DoD communication systems that are envisioned to become elements of this global network infostructure. The battlespace network includes connectivity between different ground systems (ground-ground), air and ground segments (air-ground-air), SATCOM to ground systems (space-ground-space), SATCOM to airborne systems (air-space-air), and cross-links between DoD and commercial space systems (space-space). The systems described are not all-inclusive, but they illustrate how a network infostructure can service multiple applications, lead to overall operational efficiencies, and increase capabilities through strategic leveraging of existing and planned DoD and commercial infrastructure.

4.2.1 Ground-Ground

Terrestrial communication systems, when available, provide the most convenient and generally the lowest-cost network connectivity. Wireline, fiber-optic, and wireless terrestrial communication links are the backbone of the existing DoD C^2 infrastructure. It is envisioned that DoD will continue to leverage the highly robust, secure connectivity provided by these services, adding gateways to the ground networks to provide connectivity to other DoD users operating with airborne and space communication services.

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[6] Ibid.

For example, connectivity to the Iridium mobile satellite service (MSS) network is being provided through a DoD gateway operated by the Defense Information Systems Agency, linked to the Defense Information Systems Network.

DoD has been able to leverage its large-scale use of broadband terrestrial communication services to buy access to commercial fiber networks at extremely advantageous rates. Wherever access to this ground network is available, this will provide the most cost-effective method of communication for DoD users. SATCOM and other communication links should always be restricted to applications where wireline or fiber services are not available or are impractical.

The bulk purchase of communication access as a commodity is a model that needs to be followed by the Air Force for gaining cost-effective access to commercial space services. Many of the lessons learned in this process by the NRO in negotiating terrestrial communication service can be applied for purchase of commercial SATCOM and MSS communication services.

4.2.2 Space-Ground-Space

There are several civil and military systems available for communications between space and the ground or air. These systems are generally associated with specific missions, based on the capabilities of the frequency and its international service allocation. Table I-3 lists the major commercial and military satellite services and systems that provide those services. Asterisks indicate space-air-space opportunities.

Table I-3. *Communications Satellite Services*

Type of Service	***Frequency***	***Products***	***Antenna***	***Providers***
Fixed Satellite Service Civil Geostationary Orbit	4/6 gigahertz (GHz) 11/12/14 GHz	Video delivery, very small aperture terminal, newsgathering, telephony	1-meter-diameter and larger fixed earth station	Hughes Galaxy, GE Loral Skynet, INTELSAT
Direct Broadcast Service Civil Geostationary Orbit	12 GHz	Direct-to-home video/audio	3- to 6-meter-diameter fixed earth station	DirecTV, Echostar, USSB, Astra
Mobile Service Civil Geostationary Orbit	Below 3 GHz	Voice and low-speed data to mobile terminals	Laptop computer, antenna vehicular, shipboard mounted	Inmarsat, AMSC
Mobile Service Civil (Big LEOs) Nongeostationary Orbit	Below 3 GHz	Cellular telephony, data paging, instant infrastructure	Cellular phone, pager, fixed phone booth	Iridium, Globalstar, ICO
Mobile Service Civil (Little LEOs) Nongeostationary Orbit	Below 1 GHz	Position location, tracking, messaging	As small as a pack of cigarettes, omni-antenna	ORBCOMM, ESAT
Broadband Civil Geostationary Orbits	20/30 GHz	Internet access, voice, video, data	20-cm fixed	Hughes Spaceway, Loral Cyberstar, Lockheed Martin, Astrolink
Broadband Civil Nongeostationary Orbits	20/30 GHz 10/17 GHz	Internet access, voice, video, data, videoconferencing	Dual 20-cm antennas	Celestri, Teledesic, SkyBridge
Fixed Satellite Service Military Geostationary Orbit	7/8 GHz	Trunking, video, data	5- to 18-meter-diameter fixed or transportable antennas	DSCS
Mobile Service Military Geostationary Orbit	Below 1 GHz	Voice and low-speed data to mobile terminals	Helix, flat panel, blade, and various dish antennas for mobile/fixed	Ultrahigh Frequency (UHF) Follow-On
Fixed—Broadcast Military Geostationary Orbit	20/30 GHz	Broadcast for Internet products, data, and video distribution	0.5- to 1-meter antenna fixed plus phased-array mobiles	Global Broadcast System
Assured (Low Data Rate) Military Nongeostationary Orbit	Below 1 GHz 20/44 GHz	Assured communications to fixed/mobile, low-data-rate users	UHF—same as UFO EHF—15-cm to 6-meter mobile/fixed antennas	Air Force SATCOM Milstar

The frequency allocations available to the military are a valuable commodity. They provide bandwidth guarantees and often-negotiated landing rights (authorization for use of the frequency in a host country) that are unique to the military. Due to the large requirements for communications services from space, the military will continue to depend on commercial communication satellites to provide a significant portion of its service needs. Gateways between the military systems and the commercial systems will be required to ensure seamless communications in the future.

There is no necessary connection, however, between using the military frequencies and implementing the hardware of the satellite or operating the satellite that provides that capability. Options for procuring the capability—buying the system, leasing the capacity, or becoming an anchor tenant through investment for advanced capabilities—are possible. The military must make use of the commercial capabilities first for all communication needs, saving the military-unique systems for those needs that cannot be accomplished by commercial systems.

4.2.3 Air-Space-Air

A major deficiency for the Air Force today is the lack of connectivity to its major warfighter component—the aircraft. Space communication systems are the logical choice to tie aircraft into the battlespace network. The major impediment to accomplishing this task is the lack of an affordable airborne space communications terminal.

The current use of SATCOM for air-to-space communication within the Air Force is fairly immature. A few systems (in the single digits) exist for superhigh frequency and extremely high frequency, with a limited number of systems for UHF. Receive-only systems for broadcast reception are beginning to be developed to support the Global Broadcast System.

While the cost of equipping a fleet of aircraft with a transceiver for space communications is clearly important, the driving cost is the integration of the antenna into the aircraft structure. The current desire is for a conformal phased-array antenna with all-aspect capability. This desire has not yet been realized owing to the cost of phased-array elements, fabrication of conformal antennas, off-axis performance of phased arrays, and difficulty in locating antennas on operational aircraft. The current state of the art for antennas on operational aircraft is mechanical steering by a small phased-array antenna. Integration of these antennas into an aircraft costs a significant amount and has some operational limitations.

The introduction of the Big LEO L-band commercial MSS will revolutionize access to SATCOM voice and narrowband (2.4 kilobits per second [kbps]) data services. The Iridium MSS is the first system to offer this service, shortly to be followed by Globalstar and ICO. These systems will operate at 1,610 to 1,626 megahertz (MHz), which offers an opportunity to further reduce installation costs on the aircraft by developing a multimode integrated GPS/MSS L-band antenna. Air Force aircraft are currently being equipped with dual-frequency (L1/L2) GPS antennas that operate at 1,575.42 MHz and 1,227.4 MHz. With the addition of a third antenna element, an $L1/L2/L_{MSS}$ antenna assembly can be installed on the aircraft with the same form factor as the existing GPS antenna. This approach will also require a modified radio frequency unit (RFU) to interface with both the GPS receive and the MSS receive-and-transmit radio frequency (RF) input or outputs. Investment in this modified GPS antenna/RFU could result in significantly reduced installation costs to upgrade Air Force aircraft with mobile SATCOM voice and data capability.

As described in Section 4.3, the use of aircraft (manned and unmanned) as ACNs is considered an essential element of the battlespace network. This will require access to broadband space communications. Increased investment is needed in the development of low-cost transmit or receive phased arrays for use with the broadband 20/30-gigahertz (GHz) commercial SATCOM systems, which will be operational within the next few years. Access to these GEO and Big LEO commercial SATCOM services (for example, Hughes Spaceway and Celestri/Teledesic) will provide the capability to uplink 128 kbps to 94 megabits per second (Mbps) data (depending on antenna gain) and downlink 94 Mbps to airborne platforms.

The potential also exists to use laser cross-links between high-altitude ACNs and satellites. Satellite laser cross-links are now being designed (to be available in 2002–2004) to carry 3 to 6 gigabits per second (Gbps) of data. High-altitude UAVs with laser cross-links could be designed to communicate with the National Space Communication Program (NSCP) through laser cross-links or to tie into commercial space networks.

4.2.4 Air-Ground-Air and Air-Air Communications

Air-to-ground datalinks are the predominant communication medium for tasking and accessing airborne platforms. These links are used for servicing missions, including surveillance, early-warning (EW), and fighter control missions. There are several datalinks in operation today through DoD, and a significant investment has been made in ground systems that are now tightly coupled with the C^2 structure of the Air Force, Army, and Navy. A summary of the communications datalinks in existence is provided in Table I-4. Airborne platforms will continue to be an essential link in providing assured connectivity to air and ground operations.

Table I-4. *Communications Datalinks*

Link	***Missions***	***Protection Antijam***	***Message Standard***	***Timeline Issues***
Link 16/Tactical Automated Data Link (TADIL)	Surveillance, EW, mission management, fighter control, voice and cooperative ID	Spread spectrum, frequency hop, Cyclic Code Shift Key (CCSK) pulse coding	MIL-STD-6016	None
Interim JTIDS Message Specification	Surveillance, EW, mission management, fighter control, voice and cooperative ID	Spread spectrum, frequency hop, CCSK pulse coding	MIL-STD-6016, NATO Spec ADSI RCM-D/4	Phaseout 2005
Link 11 (B)/ TADIL-A(B)	Surveillance, EW, mission management between Regional Operation Control Center and AWACS	No antijam	MIL-STD-6011	TADIL-B phaseout 2005/TADIL-A phaseout 2015
Link 4/TADIL-C	Close control between AWACS and fighters	No antijam	MIL-STD-6004	Phaseout 2005
Common Datalink	Transmits/receives data between airborne reconnaissance platforms and ground processing and combat units		Message formats based on TADIL-J	None
Surveillance Control Datalink	Communications between JointSTARS and the Ground Station Modules; wideband datalink transmits moving-target indicator and synthetic-aperture radar data		Message formats based on TADIL-J	None
Situational Awareness Data Link (SADL)/ Enhanced-Position Location Radio System (EPLRS)	Translates Link 16 data into variable message format for transmission to air-to-ground aircraft and ground-based systems; reports platform position (those equipped with SADL/EPLRS) back into the Link 16 network			None
Improved Data Modem	Transmits/receives situational awareness and targeting data between Apache Longbow and Air Force F-16 and A-10		U.S. message transfer format/ variable message format or TADIL-J	None

4.2.5 Space-Space

Satellite cross-links can be used to send and retrieve data for both payload data distribution and for C^2 of the satellite. Satellite cross-links have been very effective in reducing ground infrastructure costs for TT&C and for payload operations for large satellite constellations, such as Iridium. In order to take advantage of cross-links to maintain global operations from a small number of ground stations, a global satellite network is needed. Now that commercial space communication networks are a reality, DoD can gain space-to-space access to these networks to communicate with and control DoD-operated satellites.

The broadband laser cross-links of the near future will enable commercial and space networks to efficiently move vast amounts of data around the globe. Before Celestri and Teledesic merged, Motorola had selected a 6-Gbps laser cross-link as the baseline for that system.

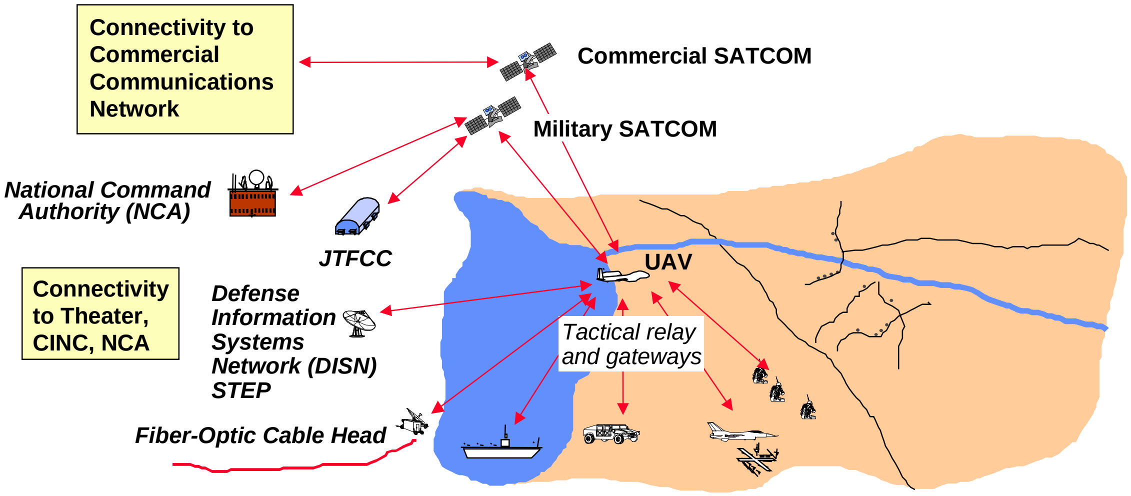
The NSCP is a joint program of military, intelligence, and civil users with space and ground assets that need to move a wide range of data from its source to its destination. NSCP architectures reviewed to date are considering the advancing technologies of LASERCOM, RF Bandwidth Efficient Modulation, and advanced optical. It is anticipated that this military space network will provide sufficient cross-link data capability to meet the future needs of U.S. space systems for data distribution.

In the future, these global high-capacity space laser networks will fulfill many of the same functions as the terrestrial broadband fiber-optic networks. It is envisioned that, as these space communication networks become prevalent, space-to-space communications will become as cost-effective as terrestrial communication links, with the ultimate bottleneck becoming the spectrum-carrying capacity of the space-ground-space RF datalinks. This ultimately will change the trade space in an MCDA for the most efficient location of such functions as information processing, fusion, and dissemination. The Payloads Appendix of this report includes a description of a ServerSAT that could perform these functions in space, reducing the required information flow through space-to-ground downlinks. The adoption of the mission-centric functionally distributed architecture will enable seamless migration among ground, air, and space nodes of the functional components needed to perform a specific mission when evolution in the communications network creates an incentive for that migration.

4.3 Gateways to Legacy Systems

For reliable, high-bandwidth data transfer, line-of-sight communications are essential, making SATCOM or ACNs the logical option. For robust operation in a jamming environment, power/aperture and distance ($1/R^2$) become the dominating factors. The shorter the distance between the communication nodes, the lower the power required to transmit at a given throughput reliability (for example, Eb/N0). Most mobile users are limited in the size of the antenna aperture they can use, and power usage of communications equipment becomes a major issue. For this reason, although commercial mobile SATCOM services will be widely used, it is envisioned that in-theater mobile communications in an electromagnetically challenged environment can be best served by ground or ACNs.

The use of an airborne platform as a gateway or relay to existing tactical datalink has many advantages. As shown in Figure I-12, it can act as a bridge between the tactical warfighter and the National Command Authority.



Satellites provide

- Tactical beyond-line-of-sight relay
- Extension of DISN to battlefield
- Global broadcast

UAVs provide

- Early-entry communications infrastructure
- Augmentation of SATCOM capacity
- DISN entry for tactical users

Figure I-12. *Airborne Communication Node*

Programs such as the ACN are developing new mobile communication systems for tactical users that will leverage advances in commercial digital cellular communication technology. The ACN payload will be carried on the Global Hawk UAV. The opportunity to use both manned and unmanned air vehicles as communication nodes and gateways to legacy ground systems needs to be fully exploited by the Air Force. A recent study performed by the Director of Satellite Communications/J-6 concluded that an ACN carried by an unpiloted combat air vehicle (UCAV) would provide capability that could not be met by existing military satellite communications (MILSATCOM) and would be more cost-effective than commercial SATCOM for both theater and tactical applications[7].

Table I-5. *UCAV/Commercial Satellite/Military Satellite Comparison*[8]

Case	***Operational Advantage***	***Technical Advantage***	***Cost***	***6-Month Operations Costs***		
				UCAV	***Com'l Sat***	***Mil Sat***
Strategic	Satellites	Satellites	Satellites	$177M	$27M	$6M
Theater	Satellite-Capacity Footprint	UCAVs Radio Relays	EQUAL Breakeven Point Is 190 Users (Commercial Satellites Only)	$177M	$105M	*
	UCAVs Connections Masking					
Tactical	UCAVs	UCAVs	UCAVs	$177M	$648M	*
* MILSATCOM cannot provide services equivalent with UCAV and commercial SATCOM for theater and tactical analysis cases						

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[7] "Unmanned Aerial Vehicles (UAVs) as Communications Platforms," Version 1.0, 4 November 1997.

[8] "Unmanned Aerial Vehicles (UAVs) as Communication Platforms," p. 19.

As the Air Force moves from a platform-centric architecture to MCDA, battle management functions that currently reside on large surveillance platforms like AWACS and JointSTARS will migrate to a distributed architecture with air, ground, and space elements. This distributed architecture is being proven by the combat training community. Air battle managers operate their consoles on the ground to control aircraft using radar data from the sector AOCs, which are distributed across their corresponding sector. Connectivity in the distributed simulation and training environment is provided by land lines.

To migrate battle managers to an operational distributed architecture would require two things: (1) relatively wideband beyond-line-of-sight data communication between the surveillance platforms (AWACS, JointSTARS) and the battle manager's location, and (2) an airborne communication switch on board the surveillance platforms to provide the translation between the network connection to the ground and the existing narrowband datalink connection to the warfighters (fighters for AWACS and ground station modules for JointSTARS). Removing the operator consoles from the surveillance platforms will provide significant design margin for additional communications functions on board these platforms.

As any tactical ISR heavy migrates to a sensor platform, it can be converted to an airborne communication hub or network server for providing information to narrowband users. This approach allows for incremental operational improvements for relatively low cost by taking advantage of existing manned platforms to act as communication nodes to the user base.

4.4 Recommendations

The development of the battlespace network will be an evolutionary process. The following recommendations are proposed to facilitate this transition and to provide the connectivity needed by the Air Force to achieve information dominance.

1. *Use commercial SATCOM services first.* Emerging commercial SATCOM services will provide global access to voice and data (narrowband and broadband) services. In many cases, these services can be adapted to meet military needs by strategic technology insertion (for example, by development of DoD gateways, modifying user equipment for "jam resistance," and negotiating priority services with commercial service providers).

2. *Develop airborne gateways to maintain connectivity with heritage tactical communications*. A significant investment has already been made in user equipment for existing tactical communications. Airborne gateways (either manned or unmanned) can provide connectivity to these heritage tactical systems as well as enhanced capability (for example, increased range of operation and connectivity for air and ground users and access to space communication services). An airborne gateway can be constructed with existing technology to demonstrate the operational effectiveness of this construct. It is recommended that an airborne gateway be developed to perform a tactical communication demonstration as part of EFX '99.

3. *Develop ubiquitous space-air-space communications*. To connect Air Force aircraft and ACNs to the battlespace network, air-space connectivity is essential. Our recommendation is to use commercial L-band MSS to introduce affordable voice and low-bandwidth data services onto Air Force aircraft. An S&T investment should be made to develop a multiuse GPS/MSS L-band antenna replacement to reduce the aircraft installation costs to achieve this voice and data connectivity. For broadband communications, an S&T investment is needed to develop a low-cost, phased-array antenna suitable for accessing the 20/30-GHz broadband commercial (and military) SATCOM services. The Air Force should take a leadership role in negotiating with the broadband civil service providers for access to their networks to establish airborne gateways to tactical datalinks.

5.0 Spiral Development: Moving to Best Commercial Practices

5.1 Introduction

The traditional DoD acquisition process is inadequate when acquiring or developing new IT products and systems. The traditional DoD process takes a minimum of 5 years, but more typically 10 years. In the commercial world, Moore's Law for integrated circuits predicts that performance will double every 2 years. This leads to a performance increase of approximately 100 times every 10 years. Selected areas of communications will increase by approximately 1,000 times over the next 10 years. Figure I-13 illustrates the gap that is created over a 10-year period when requirements are fixed and technology continues to develop at the rate of Moore's Law.

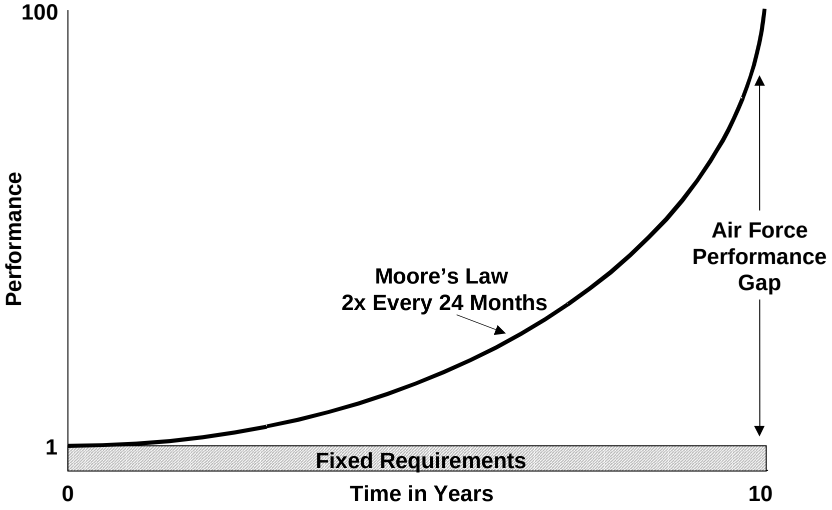

Figure I-13. *Air Force Performance Gap Due to Moore's Law*

Every 100-times increase in performance has led to a revolution in computing, from mainframes to timesharing to personal computers to graphics interfaces to networked computers to three-dimensional imaging to advanced human computer interfaces to photorealistic video.

Separate developments in computing and communications can result in surprisingly powerful systems when combined, such as in the World Wide Web. The invention of the telephone allowed one-to-one long-distance communications. The invention of radio and television allowed one-to-*n* communications. But the Web is profoundly different. It is not a telephone-television. Rather, it is a fully connected network that allows each person to broadcast to *n*, who can then broadcast to *n*. Thus, according to Metcalf's Law, this broadcast capability creates a system for which the potential value is *n* squared, as shown in Figure I-14. Understanding this and using it can create fortunes (as in the cases of Netscape and Dell) or transform the Air Force and DoD. Traditional hierarchical networks have a value proportional to *n*. Thus, exploiting the maximum power of the Web is the critical element in the Battlespace InfoSphere.

METCALF'S LAW FOR THE WEB

$$\text{Value} \propto n^2$$

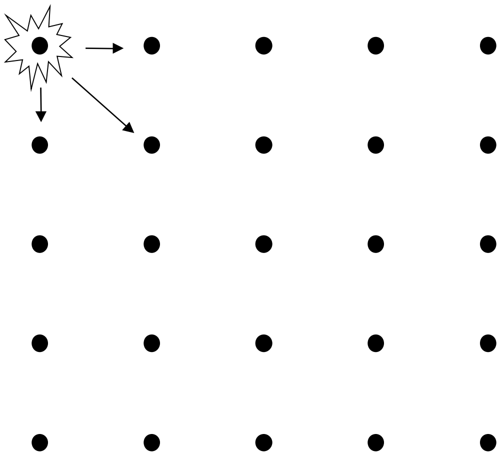

Figure I-14. *Metcalf's Law for the Web*

The *n*-squared value of the Web is just one example of the changes we can expect over the next few decades due to the compounding effects of rapid developments in IT. We should *expect the unexpected*.

The traditional government acquisition process results in obsolete IT products and systems. The Government must get within the commercial technology development cycle. The Air Force needs to create high-productivity, low-cost IT products and systems that allow timely upgrades to remain at the state of the art. That is, the Air Force must move to adopt best commercial practices.

Over the past decade, DoD has developed a family of procurement approaches and contracting vehicles, such as ACTDs to address this need. We back these initiatives and encourage the Air Force to continue to explore additional models that emulate the best commercial practices. Specifically, we encourage the wide use of SD for the rapid insertion of commercial off-the-shelf (COTS) products and the development of new IT systems and operations.

5.2 Spiral Development

SD is a process to rapidly iterate requirements and functionality with the objective of dramatically improving performance while reducing the cost of the final system or product. It starts with program goals, constraints, and requirements for minimum levels of performance. It accepts the need for change and growth in a program and allows flexibility in reaching the final objectives. It has been shown to be applicable across a wide range of technologies, products, systems, and operations. As seen in Figure I-15, SD is a process for technology acquisition that can close the gap between fixed and obsolete government requirements and rapidly evolving technology.

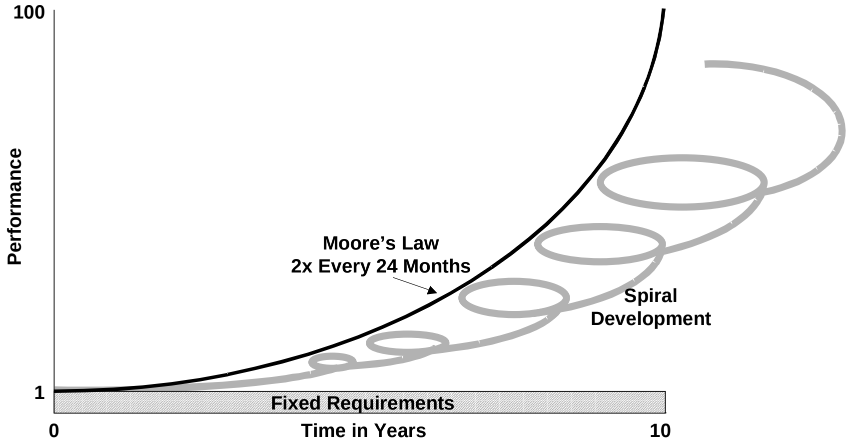

Figure I-15. *Moore's Law with SD*

The basic elements of SD are shown in Figure I-16. It begins on the left with the program goals and constraints described in the operational requirements document (ORD), which starts a process to understand in more detail user requirements, system requirements, and CONOPS. This analysis leads to function allocation to achieve the desired results. Trade studies are completed to understand the best technology alternatives, COTS products, systems, etc., leading to a baseline design and the construction of "Prototype-1."

Prototype-1 is a fielded product or system that users and operators quantitatively evaluate against formal test-and-evaluation criteria. Depending on the results of the evaluation, development is completed, stopped, or modified. Modifications start the process over again and result in new requirements, function allocation, etc. The spirals continue until the full capability described in the ORD is achieved or a decision is made to stop. As the spiral process is iterated and as performance or conditions change, new capabilities, objectives, and thresholds can be appended to the ORD.

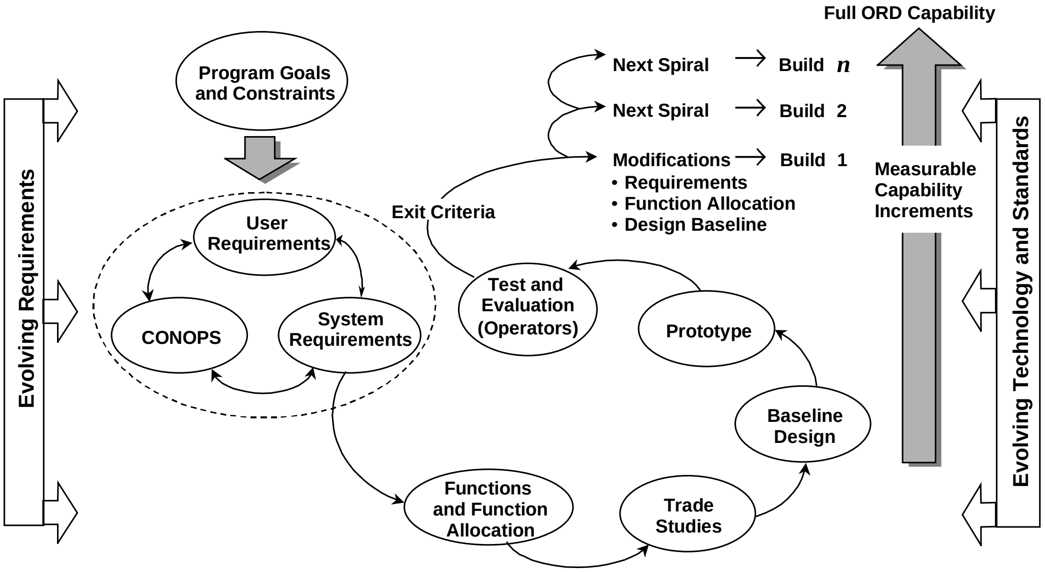

Figure I-16. *SD Process*

5.3 Spiral Development Applicability

SD creates a series of prototypes that are evaluated quantitatively by operators and, when possible, left behind to be used until the next iteration of the development process. The process can stop at each prototype milestone or continue until the project goals and constraints are achieved. It requires continuous knowledge of the state of technology. For some applications the process would continue as long as the application or mission is required.

SD is appropriate for the creation or deployment of any technology when one of the following criteria exists:

- Rapidly changing technology
- Insertion or integration of COTS products or systems
- Developing systems and systems with new operations
- Changing or uncertain operational requirements
- A need for continuous operator feedback
- Technical risk, schedule urgency, or budget-cost uncertainty (that is, when some work has been done and a decision must be made regarding how or whether to go forward)

SD can be applied at the component level or to large systems with complicated operational issues. It is particularly useful with large systems since the interaction of various elements must be evaluated as the program moves forward. SD has the additional benefit of creating a sense of urgency and responsibility in a major program. When requirements are fixed, however, normal development processes are still appropriate.

5.4 Recommendations

The Air Force must emphasize SD where appropriate in all future acquisitions. Specifically, the Air Force should

1. *Require SD for all system development and COTS integration where technology or requirements are evolving rapidly*. ESC of Air Force Materiel Command is already adopting many of these practices, and they will make a significant difference in the overall design and acquisition of the systems to which they are being applied. Most aspects of SD can be done within current requirements and acquisition process constraints but would be even more effective if legislation were sponsored to facilitate the SD process, the incorporation of rapidly developing technology, and the budgetary flexibility to recapitalize obsolete technology upgrades. The Air Force's SBIRS has started using an SD process for the predeployment phase, which is excellent but which needs to be expanded to include the entire life cycle.
2. *Include human factors considerations in the SD process for space operations*. A major change that needs to be incorporated in all SD processes is the inclusion of a human factors professional at all stages, in addition to the users/operators, engineers, and acquisition people (see Section 3.6). The SD process has been employed in many industries outside the Government. Toyota, for example, has successfully applied an SD cycle to its product development for many years.
3. *Use "Other Transactions" and innovative tools to solve contracting problems associated with SD.* Activities such as EFX '99 offer the opportunity both to try new system concepts, such as the Battlespace InfoSphere, and to prove the benefit of using an SD process for fielding current-generation capabilities to the warfighter.

6.0 Human Factors

6.1 Introduction and Problem Definition

A substantial proportion of the cost associated with the development, construction, operation, and support of Air Force space systems is related to personnel. The efficiency with which the Air Force uses its human resources in accomplishing terrestrial operations is therefore a pivotal factor in determining the affordability and mission capability of the 21st-century Aerospace Force. The terrestrial segment study team addressed human factors issues as they impact current Air Force space operations and made recommendations for the Air Force leadership to strengthen overall mission effectiveness.

The study team made a number of site visits and received briefings and demonstrations from a variety of agencies within DoD and the aerospace industry (see Figure I-17).

Space Operators

- 50th Space Wing (including Space Operations Squadron tours)
- COMSAT
- Iridium operations center
- Air Force Space Command
- Air Force Satellite Control Network

Space Users

- Navy Space Command
- Defense Intelligence Agency Central Measurement and Signature Intelligence Office
- NIMA
- Army Space Command
- C^2 Technical Integration Center
- Army Common Ground Station
- Multisource Tracking System/Combat Track
- JTAGS
- Attack and Early Reporting to Theater

Development/Acquisition Organizations

- Electronic Systems Center
  - Spiral Development
  - Theater Battle Management Core Systems
  - AWACS
  - JointSTARS
  - Eagle Vision
  - Commercial SATCOM
  - Force Protection
- Defense Airborne Reconnaissance Office
- NRO Information Superiority
- Joint Intelligence Virtual Architecture
- Office of the Secretary of Defense Architecture Coordination Council
- Air Force Battlelab
- Space Warfare Center
- Boeing Airborne Early Warning Crew Systems
- NRO National Space Comm Program
- DARPA Dynamic Database
- Air Force Research Laboratory
- Defense Information Systems Agency

Figure I-17. *Site Visits and Briefings*

Information sources were selected to obtain a balance of perspectives from those organizations most concerned with the operational effectiveness of the terrestrial segment of space systems, including

- Operation of space platforms and payloads
- Use of products provided from or through space
- Design, development, and procurement of space systems

The information obtained from these sources showed a lack of sensitivity to human factors issues and a pervasive lack of awareness of the potential benefits to be gained from good human engineering design. While the study participants were generally supportive of the need to place more emphasis on human factors, the enabling infrastructure for improvements (policies, processes, skills, etc.) is not currently in place within the military space community. Some of the major study observations regarding human factors in contemporary Air Force space systems are summarized below. Specific examples are listed in Figure I-18.

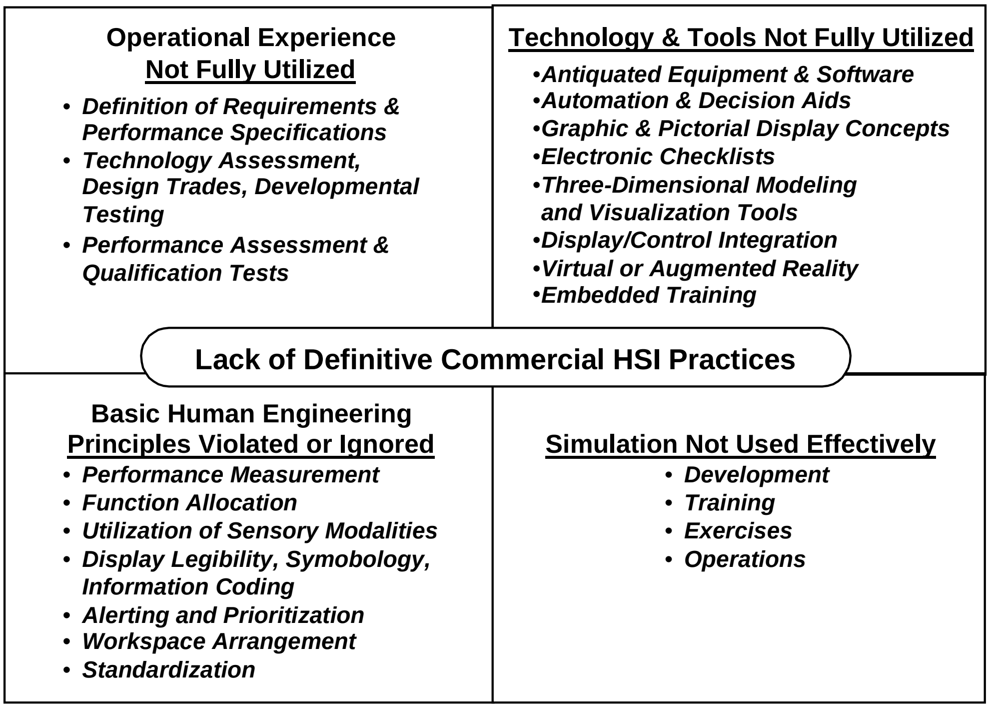

Figure I-18. *Findings*

Operational Experience. Developers have not fully used operational experience with prior systems in the design and development of new space systems. Systematic documentation and application of lessons learned is lacking. Operators and human factors specialists are not an integral part of the acquisition process.

Human-System Interface (HSI) Technology and Tools. A number of HSI technologies and software tools are readily available and have demonstrated their usefulness in military and industrial applications. While many of these HSI technologies have been used to great advantage to reduce workload and improve situation awareness in other Air Force missions, they have been underutilized in space system applications.

Human Engineering Design Principles. A large body of knowledge regarding HSI design exists as human engineering standards, guidelines, and research reports. Developers have generally not applied this information effectively in the design of space systems. Where commercial standards or "style guides" have been applied, they tend to be inconsistent across suppliers and do not fully address many military-unique requirements. As a consequence, developers have violated basic human engineering principles, resulting in deficiencies in key areas that may impact operational effectiveness.

Acquisition Process. The lack of attention to human factors in the design of contemporary Air Force space systems is fundamentally a process problem. The full integration of human engineering design principles and practices into the acquisition cycle represents a significant opportunity to enhance the cost-effectiveness, readiness, and mission capability of these systems with a modest investment of resources.

Impact of Human Factors. It is evident from the findings of this study that the potential impact of human factors on productivity, affordability, and mission-effectiveness of Air Force space systems is substantial. It is also apparent that this potential is not being fully realized. While the knowledge base and enabling technologies are readily available, developers are not applying them in a comprehensive or systematic way in the acquisition of space systems. The following are some of the consequences of overlooking human factors:

- Resources
  - Personnel: Need for additional staff to compensate for HSI deficiencies
  - Equipment: Inefficient management of costly, high-demand assets
  - Software: Underutilization of automation capability
- System Performance
  - Increased potential for error during emergency and contingency operations
  - Performance decrements under high workload (for example, wartime surge)
  - System capacity limitations (HSI bandwidth)
- Personnel skills and training
  - Increased training costs and schedule impact
  - Limitations on how personnel can be used (for example, cross-training)
  - Potential for negative transfer of training
  - Decrease in retention of skilled personnel

The study team has concluded that there are significant opportunities to improve the utilization of human resources in future space systems. These opportunities fall into three general categories:

- Development and applications of human performance metrics
- Integration of human factors with the acquisition process
- Cost-effective human-in-the-loop simulation

6.2 Human Performance Metrics

Measurement is essential in the design, development and testing of systems. The establishment and routine application of quantitative criteria to assess such mission-critical attributes as accuracy, processing speed, reliability, and durability is an accepted practice in the acquisition of Air Force systems. The use of performance metrics to assess the mission-effectiveness of HSI has not been fully institutionalized in the acquisition process for space systems. As a consequence, the Air Force leadership does not have definitive indices to assess how effectively the human resources are being utilized in accomplishing a given mission. Therefore, where division of responsibility between humans and automation, investments in HSI upgrades, staffing, and training are concerned, decisions and tradeoffs must be made on a largely subjective basis.

While measurement of human performance presents some unique challenges, practical and useful tools have been developed and used to great advantage in other military and commercial applications. These include aircraft crew stations, aircraft maintenance and servicing provisions, and nuclear power plant control stations. As systems become more complex, measurement can become more difficult, but it can still be accomplished by skilled human factors practitioners.

Measurement of human characteristics is difficult because physical characteristics and behavior vary, not only from person to person but also at differing times within the same person. Program managers have sometimes concluded that humans are so adaptable and so variable it is beyond their managers' purview to include in the design process a systematic approach to maximize human effectiveness.

The flexibility of the human is vital to system performance in reacting to unforeseen circumstances and as a backup to other system failures. Decision making is becoming the dominant role of humans in modern systems. Measurement of human abilities is necessary to allocate functions and evaluate design concepts. It is also important in providing precision feedback for training. Many people assume that automation and computers are a way to reduce costs. Computers, however, are not capable of inductive or extrapolative reasoning. It is increasingly important to maximize the quality of human performance in the observe-orient-decide-act loop in order to minimize errors and the cost of system development, operations, and support.

The uncertainty associated with human performance measures falls into two areas: measurement precision and the weight of the various performance elements. Statistical methods, however, can help achieve meaningful and useful levels of precision. Even complex assessments involving many factors can be assessed in the context of system development using multivariate techniques.

The Air Force and developers must select performance attributes and measures that are valid to mission performance, or decision criteria may be biased toward less desirable goals. Psychometric psychology has developed many useful and reliable measures.

To establish specific human performance requirements for systems and assure that these are met in system development, appropriate human performance metrics must be defined. Figure I-19 offers some examples of performance measures related to specific human functions and tasks. To assure that the desired value of the measurements is achieved is not a trivial task and will require a cooperative effort among the operators, designers, and qualified human factors specialists.

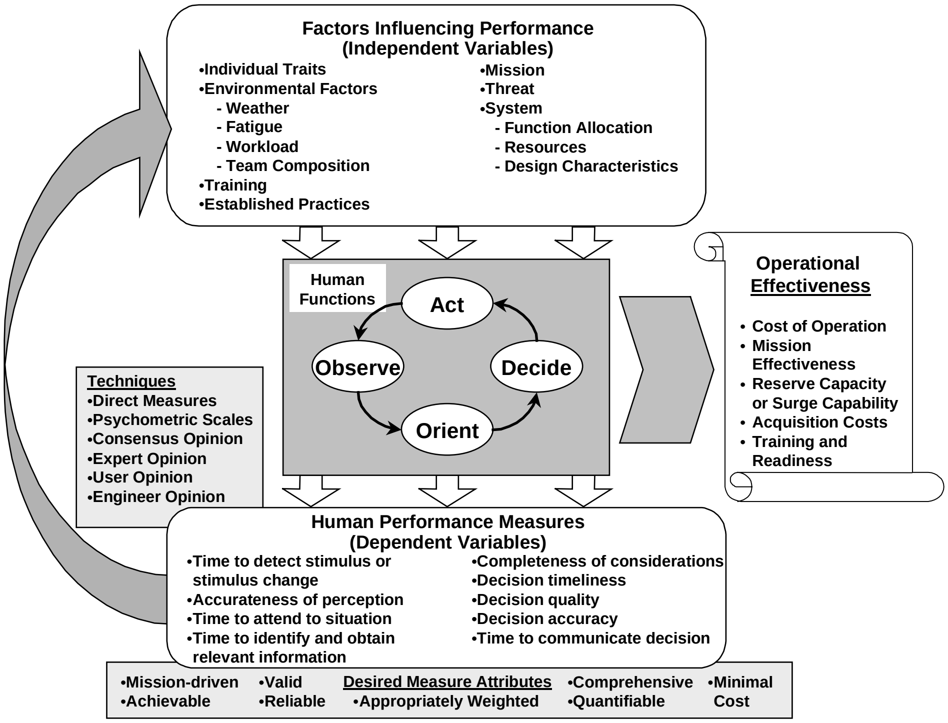

Figure I-19. *Human Performance Measurement*

Once users and developers define appropriate metrics for a specific system, they can use these metrics to assure that the system meets the human performance requirements. The more precise and comprehensive the measurements, the better the feedback and the less the subjectivity in the results. In addition, the same measures will be available to enhance and evaluate the development and performance of training systems.

6.3 Human Factors in the Acquisition Process

In order for the Air Force to integrate an effective, value-added human factors program into the acquisition process, the implementation must accommodate the realities of funding constraints, rapid evolution of technology, and the changing nature of Air Force procurement practices. Such a program should

- **Be affordable:** Acknowledge realities of budget and schedule constraints
- **Be flexible:** Adapt to the nature of the procurement
  - Conventional full-scale engineering development (FSED)
  - SD
  - Advanced Technology Demonstration (ATD)/ACTD
- **Encourage active involvement:** Provide a mechanism for full integrated project team participation
  - Procurement authority
  - Developers
  - Human factors specialists
  - Operators
- **Use best practices** (military and commercial)
  - Performance-based specifications
  - Objective, mission-driven performance criteria (metrics)
  - Rapid prototyping and developmental testing
  - Selective military and commercial standards
- Fully address all essential program elements
  - Hardware development and support
  - Software development and support
  - Personnel skills and training
  - Operating environment

Within the context of major weapon system procurements, developers have traditionally addressed human factors as part of the system engineering element of the work breakdown structure when they have addressed it at all. With the trend toward streamlined procurement practices, and the use of ATD and ACTD in the initial stages of development, these system engineering activities have been deemphasized or omitted from the front-end effort on new programs. This trend presents a major obstacle to effective human engineering, since the opportunity for return on investment is greatest in the early stages of development.

The SD approach to acquisition provides a framework within which the Air Force can implement a practical, cost-effective human engineering program consistent with the criteria listed above. The SD concept embodies several characteristics that facilitate effective human-system integration.

- SD is an iterative process that can accommodate rapid change in technology and standards
- SD responds to changes in doctrine, CONOPS, and mission requirements
- SD provides early and frequent opportunities for user involvement and feedback
- SD provides frequent products that can be used for field tests and demonstrations

Figure I-20 shows a simplified model of the SD approach and identifies the key insertion points for human factors principles, design criteria, and methods.

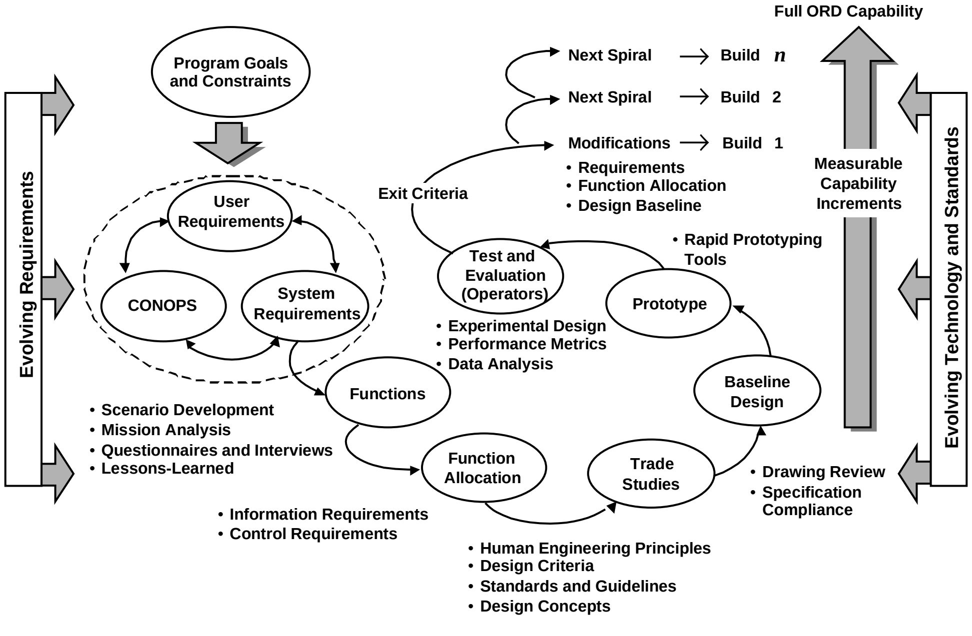

Figure I-20. *Human Factors Contributions in the Spiral Development Process*

The SD process places substantial emphasis on early involvement of users in the initial definition of system requirements and CONOPS. Human factors specialists can facilitate this process through well-established methods for deriving functional requirements and documenting relevant operational experience. If applied systematically, human factors principles can also help to assure an optimum allocation of functions between humans and automation. As the system concept evolves, human engineering design criteria support trade studies and downselect of design alternatives. Human performance metrics serve as the principal means for quantitative assessment of prototypes in part-task simulation. The iterative nature of the SD model enables frequent user feedback as the technology and design concepts mature. In this way, developers can identify and correct deficiencies at the earliest possible stage of development, minimizing impact on cost and schedule.

In order to realize these potential benefits, human factors must become an integral part of the acquisition process from initial requirements definition to operations and subsequent product upgrades. It is essential that the resources committed to the human factors effort be proportional to the potential impact on mission effectiveness and affordability of the product.

6.4 Cost-Effective Use of Simulation

Developments in simulation technology have greatly improved the utility and affordability of human-in-the-loop simulation tools. Designers or operators can simulate complex operations and display representations “hands-on” without the need for expensive, time-consuming programming support. This technology can provide a common environment in which trainers, operators, and developers can work in concert to solve problems, incorporate new functionality, and accommodate changing mission requirements while minimizing cost and cycle time.

Contemporary desktop simulation tools

- Are optimized for hands-on use by designers (requiring minimal support from skilled programming specialists)
- Consist of relatively low-cost software that runs on commonly available platforms (including some high-end personal computers)
- Use a flexible HSI that includes various options for control of discrete or continuous operator inputs (for example, cursor control, joysticks, and touch-sensitive overlays)
- Are designed for utility in creating system simulations and varying input or output parameters
- Are transferable programs
- Offer flexibility in linking to existing system and subsystem models
- Accommodate networking
- Have an integral capability to record and analyze human performance data

The Air Force is using these tools to great advantage in such areas as

- The design and testing of cockpits for aircraft (single and multicrew positions)
- The design and testing of mission crew stations for airborne EW aircraft
- The development of ground crew station concepts for UCAVs

In these applications, part-task simulation is used to engage users early in the development process and to obtain feedback on alternative concepts at a point at which changes are most affordable and schedule impact is minimal.

The findings of this study suggest that the Air Force is not using human-in-the-loop simulation to maximum advantage in space applications. Areas for potential use include

- Design trading and comparative assessment
- Development of procedures
- Embedded training
- Proficiency and skill maintenance
- Three-dimensional visualization
- Diagnostics and troubleshooting
- Operational exercises

In addition to these specific areas of application, low-cost simulation may provide a mechanism to more effectively integrate the contributions of engineers, operators, programmers, and human factors specialists during the development of systems. Figure I-21 illustrates how the Air Force could use rapid prototyping tools, part-task simulations, and a simulation network to facilitate cooperative development and testing of new concepts. Design tools can directly aid system development, while trainers can benefit from system simulators. Operators can more quickly address system errors through diagnostic tools. In addition, embedded training capabilities can help operators and trainers in their daily activities. Finally, the networked simulations can support all aspects of a system's life cycle, from cooperative development, to test, to training, to operations.

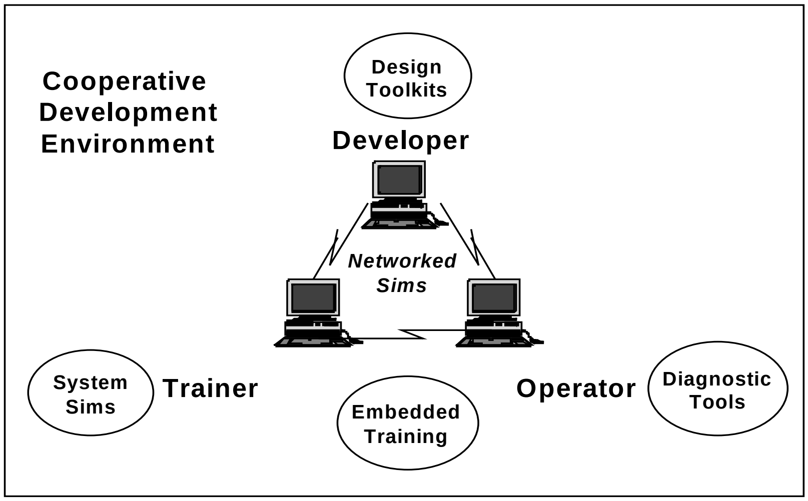

Figure I-21. *Cost-Effective Use of Simulations*

6.5 Human Factors Awareness

Developers design all systems to serve the human in one form or another. The Air Force acquires information systems primarily to assist the human in assimilating relevant information, making rapid accurate decisions, and communicating these decisions to others. In turn, human factors facilitate this process. Human factors are critically important for space systems to ensure that the right information is at the right place at the right time in the proper format. Figure I-22 shows elements of a space system impacted by human performance.

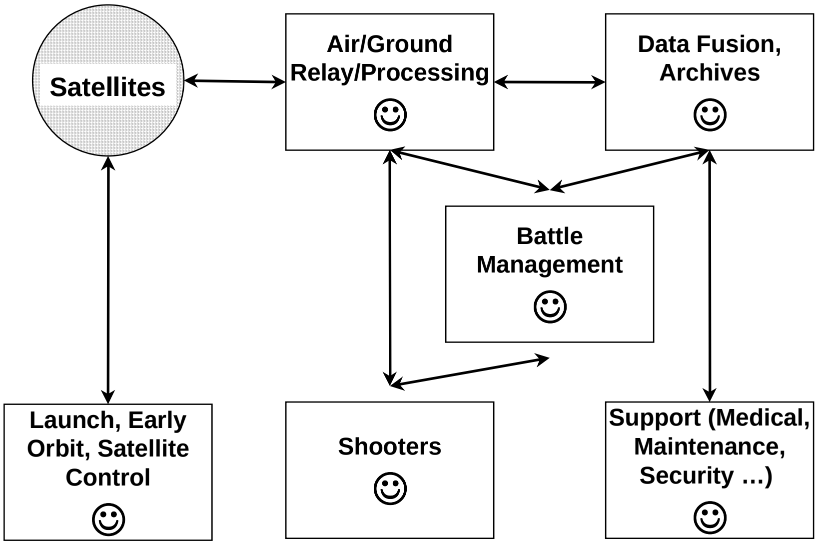

Figure I-22. *Human Involvement in Space Systems*

To maximize the effectiveness of human factors engineering, developers need to include human factors specialists throughout the total life of a system from the earliest concept stages (see Figure I-20).

The cost of implementing a human factors program need not be great. Return on investment for systematically applying this field may be greater than for any others. Many of the facilities required, such as simulators, are developed too late in the program to help front-end decisions. Rapid prototyping and testing will enable developers to make decisions that will reduce late engineering changes. Staffing requirements are not large compared to other disciplines (one recent, reasonably effective program had 0.05 percent of the engineering budget). If the Air Force systemizes the professional application of human factors, significant improvements in such decisions as crew size will have a great impact on life-cycle costs.

The Air Force has recognized the value of a professional human factors effort in the development of some systems. Human factors are receiving considerable emphasis, for example, in the UCAV program. Steps have been taken to increase the consideration of human factors issues in ACTD programs. Many of the same principles and methods could be used to address human-system integration issues in Air Force space systems. Table I-6 lists some current human factors challenges for Air Force space development.

Table I-6. *Some Current Human Factors Challenges*

Area	*Challenges*
Operators	Situation awareness Information overload Input errors Fatigue Underload and boredom Inefficiency
Personnel and training	Offline training opportunities Keeping current Career field definition Selection and requirements Cross-training Turnover Training enhancements
Design methods and requirements	Automation Function allocation Intuitive display development Capability enhancements Incorporating changes after initial design Performance goals and measures

Data are not information. Data are external to the human; information is internal. Human-machine systems must integrate data with people's training and experience to convert the data to information. The goal of the human factors portion of this study was to make certain that the information war is won by assuring that the right information reaches the right people at the right time in the right format to facilitate fast and accurate information transfer.

6.6 Recommendations

To obtain the full benefit of human factors issues, the Air Force should pursue the following:

1. Task the Air Force Research Laboratory, the product centers, and the Major Commands (MAJCOMs) to develop and apply measures of human effectiveness in

- Defining system requirements
- Assessing design alternatives
- Quantifying return on investment for HSI upgrades
- Test and evaluation
- Training and exercises

2. Task all elements of the acquisition system, including requirements, development, and logistics support, to incorporate human factors as an integral part of SD

- Tailor the human factors program to type of procurement (FSED, ATD, ACTD, etc.)
- Incorporate human performance metrics in system performance goals and test criteria
- Mandate inclusion of qualified human factors specialists and representative operators as full participants throughout the acquisition process
  - Require MAJCOMs to fully address human factors issues in concept, program requirements, and CONOPS development.
  - Require product centers and logistic centers to fully address human factors issues in all development plans and work breakdown structures. Include contractor tasking and resources to fully address human factors issues in all program phases (for example, requirements definition, design, evaluation, and product improvements).

3. Task product centers and operational commands to leverage state-of-the-art simulation capabilities to integrate and test HSI throughout the SD process using consistent groups of representative operational personnel

- Rapid prototyping
- Part-task simulation
- Onsite user enhancements (including tie to configuration management system)

4. Task training and operational commands to use cost-effective human-in-the-loop training to develop basic and system-specific skills and improve overall readiness of operational personnel; take full advantage of modern tools and techniques

- Embedded training
- Three-dimensional visualization (including virtual or augmented reality)
- Simulation networks

5. Task operational commands to exploit simulation in conducting routine operations, participating in exercises, managing contingencies, and maintaining proficiency in key skills

- Embedded training
- Diagnostics and troubleshooting on-orbit problems
- Mission preparation and rehearsal
- Operational exercises, surges, and contingencies

6. Increase the awareness of human factors

- Provide top-down advocacy

- Include human factors elements in the required Defense Systems Management College acquisition courses (for example, ACQ-101, ACQ-201)

- Provide methods and material for government personnel and contractors involved in Air Force system acquisition

7.0 Conclusions and Recommendations

Commercial space products and services now offer tremendous opportunities for DoD to change the way it does business. The dramatic increase of commercial capabilities, especially communication and imaging systems, offers opportunities for national defense systems in both capabilities and operational practices. The Air Force, as the largest provider of space products and services for DoD, must take the lead in exploiting the benefits offered by commercial space. The Air Force should streamline satellite operations by transitioning to a commercial model for staffing and system operation, outsourcing noncritical functions; separating payload control from TT&C to allow optimization in each area; and making selective investments in ground equipment upgrades where justified by personnel savings and other benefits. Since the Air Force is now in a position to consume and use technology, rather than create it, we must learn to *use commercial first* rather than using commercial systems as a supplement. Specifically our recommendations are to

Adopt and exploit commercial satellite operations technology, practices, and services.

- Get on board early with commercial space initiatives

- Use commercial infrastructure and satellite buses where possible to support military payloads

- Use the SD process to take advantage of continued evolutionary improvements driven by commercial investments

- Use commercial operating practices to gain operational efficiency

Military operational effectiveness can be greatly improved by taking a mission-centric (or capability-centric) view across a system-of-systems architecture including air, space, and terrestrial components. This evolutionary migration from a platform-centric view can enable new capabilities and expanded services while maintaining backward compatibility with existing infrastructure and user equipment. In order to enable this vision we specifically recommend that the Air Force

Migrate from a platform-centric to a mission-centric distributed architecture

- Establish a collaborative, Web-like environment to enable distributed mission operations that can fuse data across sensor modalities and support system-of-system (air and space) tasking

- Migrate to a network-centric space-based communications structure to provide global connectivity for integrated aerospace missions

The implementation of a mission-centric distributed architecture relies on connectivity between the planning, sensing, processing, and user elements (or nodes) of the battlespace network. This requires that serious attention be paid to connecting all components of the Air Force's existing assets that provide information to contribute to this distributed environment. Specifically we recommend that the Air Force

Establish connectivity for the network-centric battlespace

- Use commercial SATCOM services first, and negotiate with service providers to adapt systems where possible to meet military needs through technology insertion
- Develop airborne gateways to maintain connectivity with heritage tactical communications
- Develop ubiquitous space-air-space communications to tie all Air Force aircraft into the battlespace network

It has been shown that the traditional DoD acquisition process is inadequate when acquiring or developing new IT products and systems. The traditional DoD process takes a minimum of 5 years for development, while in the commercial world, typically performance improvements of 100 times are being recognized every 10 years. The Air Force should make both a revolutionary change to switch from military to civilian models for system development, procurements and operations, and an evolutionary change based on continuous planned improvement throughout the program, using the SD process as a model.

Emphasize SD in future acquisitions

- Require SD for all system development that can leverage commercial investments that are resulting in rapid evolution of technology
- Include human factors considerations in the SD process for space operations
- Use "other transactions" and innovative tools to solve contracting problems associated with SD, such as have been applied in EFX '99

The human factors area remains a perennially neglected discipline, with serious long-term consequences. Poorly designed operator stations and other aspects of the human-system interface impact everything from the effectiveness of system operation to training requirements to morale. The root problem is that neither the Government nor contractors treat human factors as a critical aspect of system requirements and a mandatory element of the system engineering process. As long as the problem is ignored, a host of unnecessary costs, many of them hidden, will continue to be paid. To resolve this problem, we recommend that the Air Force

Incorporate human factors as an integral part of the acquisition process

- Develop and apply quantitative measures of human effectiveness in all system development
- Use human-in-the-loop simulation to improve the effectiveness of development, training, exercises, and system operations

Annex to Appendix I

Acronyms and Abbreviations

AB	Air Base
ACN	Airborne Communication Node
ACTD	Advanced Concept Technology Demonstration
ADS	Autonomous Dependent Surveillance
ADSI	Air Defense Systems Integrator
AEF	Aerospace Expeditionary Force
AFB	Air Force Base
AFSCN	Air Force Satellite Control Network
AMSC	American Mobile Satellite Corporations
ANG	Air National Guard
AOC	Air Operations Center
AS	Air Station
ATC	Air Traffic Control
ATD	Advanced Technology Demonstration
ATO	Air Tasking Order
AWACS	Airborne Warning and Control System
BADD	Battlefield Awareness and Data Dissemination
BDA	Battle Damage Assessment
BM	Battle Management
BMC^4I	Battle Management Command, Control, Communications, Computers, and Intelligence
C^2	Command and Control
C^4I	Command, Control, Communications, Computers, and Intelligence
CCSK	Cyclic Code Shift Key
CGS	Common Ground Station
CINC	Commander in Chief
CMS	Cape Monitoring System
CONOPS	Concept of Operations
CONUS	Continental United States
COTS	Commercial Off-the-Shelf
CUE	Common User Equipment
DARPA	Defense Advanced Research Projects Agency
DISN	Defense Information Systems Network
DoD	Department of Defense
DSCS	Defense Satellite Communication System
EFX	Expeditionary Force Experiment
EHF	Extremely High Frequency
ELINT	Electronic Intelligence
EPLRS	Enhanced-Position Location Radio System
ESC	Electronic Systems Center
EW	Early Warning
FSED	Full-Scale Engineering Development
G/S	Ground Station
GANS	Global Air Navigation Systems
GATM	Global Air Traffic Management

Gbps	Gigabits per Second
GEO	Geosynchronous Earth Orbit
GHz	Gigahertz
GMTI	Ground Moving-Target Indicator
GPS	Global Positioning System
GTACS	Ground Tactical Air control System
HMI	Human-Machine Interface
HQ	Headquarters
HSI	Human-System Interface
ICO	International Communications Organization
ID	Identification
IMINT	Imagery Intelligence
ISR	Intelligence, Surveillance, and Reconnaissance
IT	Information Technology
JFACC	Joint Forces Air Component Commander
JointSTARS	Joint Surveillance, Target, and Attack Radar System
JTAGS	Joint Tactical Ground Station
JTFCC	Joint Tactical Forces Command and Control
JTIDS	Joint Tactical Information Distribution System
Kbps	Kilobits per Second
LASERCOM	Laser Communication
LEO	Low Earth Orbit
MAJCOM	Major Command
Mbps	Megabits per Second
MCCC	Mobile Command and Control Center
MCDA	Mission-Centric Distributed Architecture
MHz	Megahertz
MILSATCOM	Military Satellite Communications
MMCCS	Milstar Mobile Command and Control System
MSS	Mobile Satellite Service
NATO	North Atlantic Treaty Organization
NCA	National Command Authority
NIMA	National Imagery and Mapping Agency
NRO	National Reconnaissance Office
NSCP	National Space Communication Program
OCMC	Overhead Collection Management Center
ORD	Operational Requirements Document
OSI	Open Systems Interconnect
PCS	Personal Communications System
POM	Program Objective Memorandum
QoS	Quality of Service
RCC	Regional Contingency Center
RCM D/4	NATO message formatting standard
RF	Radio Frequency
RFU	Radio Frequency Unit
S&T	Science and Technology
SAB	Scientific Advisory Board
SADL	Situational Awareness Data Link
SAM	Surface-to-Air Missile
SATCOM	Satellite Communications
SBIRS	Space-Based Infrared System

SD	Spiral Development
SEAD	Suppression of Enemy Air Defenses
SIGINT	Signals Intelligence
SMC	Space and Missile Systems Center
SSI	System-of-Systems Interconnect
STRATCOM	Strategic Command
TADIL	Tactical Automated Data Link
TBMCS	Theater Battle Management Core System
TT&C	Tracking, Telemetry, and Control
UAV	Unmanned Aerial Vehicle
UCAV	Unpiloted Combat Air Vehicle
UFO	Ultrahigh Frequency Follow-On
UHF	Ultrahigh Frequency
USSB	United States Satellite Broadcasting
VCE	Virtual Computing Environment

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Appendix J

Cost and Acquisition Strategy

1.0 Executive Summary

The Cost and Acquisition Strategy Panel was tasked to forecast costs associated with the Summer Study's recommendations. Since this was the first such undertaking in recent memory, the panel was challenged with new ground in a number of areas. Among them were implementing the process of cost estimating, interfacing with other study panels to collect and analyze system information, developing tools for cost estimation, and presenting the results at the correct level of detail, with appropriate qualifications. Despite the uncertainty of predicting the needs and costs 20 years into the future, the panel rose to the challenge, providing the required answers for the study while setting in place a procedure and tools for establishing cost estimation as a permanent element of the Summer Study.

With support from Tecolote Research, Inc., the panel employed the cost-estimating tools required to estimate space system costs. Tecolote's Advanced Cost Estimator Integrated Tool (ACEIT) model was modified and used throughout this study. A technical readiness matrix was applied in a limited fashion to ACEIT, modifying the "most likely" costs, to account for the historical cost growth of high-risk programs. The model was then used to estimate costs of new programs, specifically an Aerospace Operations Vehicle (AOV) and a STARLITE-like space-based radar (SBR).

Results of the modeling indicate that current budgets and current "ways of doing business" will not support these systems proposed by the Air Force Scientific Advisory Board (SAB). Instead the panel considered cost-reduction options that reduce, eliminate, or transfer responsibility for activities not central to warfighting from space, and found them to significantly offset the costs of these systems. In addition, the panel investigated and recommended acquisition strategies and innovative uses of commercial capabilities to reduce total "Going to Space" costs.

It is important to realize that the cost estimates represent the best efforts of a dedicated and competent team, but one that concentrated its efforts over a very short period and was undertaken on the basis of "volunteer labor." The estimates for the cost of two of the new systems are based on a rigorous model that has been validated for use in a variety of Air Force programs. It was used for the SBR and AOV programs, for which the Launch and Payload Panels were able to provide sufficient definition. Since sufficient detail on system definition was not available for the ground-based laser (GBL), the estimate for that program was provided to the Cost and Acquisition Panel by the Space Control Panel. Clearly, our estimates are not accurate enough for investment decisions. However, we do think they provide a good insight into the magnitude of investments required.

The estimates of potential savings were arrived at in a totally different manner. The "moderate reduction" estimate was based on savings options identified by this and other panels. We applied generic planning factors and historical experiences to estimate the level of savings. These should be considered rough order-of-magnitude estimates. The "aggressive reductions" estimates were based on maximum possible savings from initiatives recommended by the Operations Panel. These reductions essentially involved zeroing out activities, assuming that those operations or services would be provided from outside the Air Force budget.

The study recommends that the Air Force undertake detailed cost studies of the potential savings outlined in this report before even preliminary decisions are taken on implementation.

1.1 Introduction

This report is a forecast of the potential future of the U.S. Air Force. This forecast does not necessarily imply future programs, planning, costs, or policies that are officially sanctioned.

In the 52 years of the SAB, we have made estimates of the future and technology. We understand the uncertainties that accompany any attempt to predict the future. Most predictions become increasingly inaccurate after a decade or so has passed. In that respect, this study is no different from those that have preceded it; however, this is the first SAB study to add the dimension and complication of cost estimation.

In today's world, we assert that "affordability" must be emphasized as much as technology, for it is the hard-earned dollars of the American taxpayer that pay for our national security. In the Cold War, a monolithic threat and potential scenarios were well known. But in the current and expected cost-constrained budget environment, we must train and equip our military forces for a diverse set of situations across the full spectrum of conflict. These constraints require that cost and performance of competing potential systems be evaluated and compared.

With an environment of limited dollars and competing solutions to ill-defined problems, we must evaluate the rising capabilities of commercial technologies and enterprises as we consider divestiture of support functions. This brings another dimension to the cost-effectiveness analysis of any force options, and requires new approaches to meeting Air Force goals.

Lord Rutherford once said, "We are out of money and thus, we must think." This study represents that thought process. Other panels addressed the capabilities enabled by the new technologies we envision. Here we delineate the cost methodology and the relative costs of those envisioned force options. We also consider alternative means of acquiring necessary capabilities.

1.2 Cost and Acquisition Strategy Panel Membership

Mr. Tom McMahan, Chair
Co-President
Modern Technology Solutions, Incorporated

Professor John C. Doyle
California Institute of Technology

Dr. James D. Lang
Director of Flight Technology Integration
The Boeing Company

Mr. Mel Eisman
Senior Cost Analyst
The RAND Corporation

Mr. John J. Welch
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Mr. James E. Vint
Manager, Office of Strategic Business Planning
Lockheed Martin Missiles and Space

Dr. Barry Zilin
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Advisors:	Brig Gen James Beale, SAF/AQS
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	Maj Denise Knox, SAF/AQSP
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Executive Officer: Capt Charles E. Hogan, II, HQ USAF/XPY
Technical Writer: Maj Thomas E. McLaughlin, USAFA

1.3 Cost and Acquisition Strategy Panel Charter

The Cost and Acquisitions Strategy Panel will:

- Develop a cost estimation methodology for the study and for applying that methodology to quantify the costs of the options that are developed.
- The panel will assemble and, as appropriate, expand upon existing cost models and cost-estimating relationships (CERs) and will seek to assemble the most complete database feasible on the current and projected costs of hardware, software, and services.
- The panel will seek to establish a basis for valid comparisons among alternatives, for example, placing a given function on an orbiting or airbreathing platform for a given level of service to customers. The panel will consult both Government and industry organizations in attempting to compile this cost estimation basis.
- The panel will address alternative acquisition strategies in light of the rapid evolution of the space community and industry, the paramount importance of affordability, the practical aspects of migration and progressive replacement of terrestrial functionality, acquisition reform, and the need to accelerate the cycle of defining, developing, and fielding space capabilities.

1.4 Structure of the Appendix

This panel’s task was to project costs of potential programs and recommend acquisition strategies to acquire them. To estimate the costs associated with space assets over the next 20 years, appropriate tools had to be gathered and modified. Section 2.0 describes the cost estimation tools used, the methodology undertaken to estimate costs for the study, and the assumptions used to arrive at cost estimates for future space capabilities. Section 3.0 describes the results of the estimation process, and compares costs of several different scenarios. Section 4.0 summarizes recommendations based on that study. Section 5.0 discusses findings derived from the cost estimates generated, and Section 6.0 makes recommendations to mitigate those findings.

2.0 Cost Estimation Methodology

2.1 Introduction

The cost-estimating methodology described in the sections that follow was selected with the objective of providing the most complete and representative costs relative to the funded baseline for recommended new programs and possibly offsetting savings through new strategies. For comparison, the funded baseline used the Air Force President's Budget (PB) as of January 1998 to cover the costs through fiscal year 2003 (FY 03). This funding was further extended for FY 04–20, based on straight-line funding with 2.2 percent inflation per year for ongoing programs and straight-line ramp-down for programs known to be planned for phaseout prior to FY 20. For FY 04 and FY 05, tailoring for planned changes was included.

2.2 Cost-Estimating Architecture

The baseline and other option program-level cost estimates were stratified across eight subarchitecture elements and further subdivided into space- or terrestrial-based segments. The subarchitecture level elements are infrastructure; environmental; launch; intelligence, surveillance, and reconnaissance (ISR)/ warning; space control; navigation; infostructure; and force application.

The first option, referred to during the study as "Baseline Plus," added three new systems to the baseline: a GBL, an SBR, and an AOV. From there, two further options considered offsetting savings from aggressive and moderate cost reductions that reduce, eliminate, or transfer responsibility for activities not central to space warfighting.

The estimates are time phased and summarized as annual budgetary estimates subtotaled across the eight subarchitecture elements and across major budget appropriation categories. These include research, development, test, and evaluation (RDT&E); procurement; operations and maintenance (O&M); and military personnel (MILPERS). These estimates are graphically summarized in Figures J-1 to J-6.

The option costs relative to the baseline are derived by extracting key elements of each enhanced or new system. These elements establish the

- *Legacy*, including civil/commercial, modified civil/commercial, or government off the shelf
- *Features*—capabilities relative to the baseline or in absolute terms
- *Physical parameters* in terms of estimated or assumed weight, power, density, software lines of code, and, if possible, associated relative technical complexity to a similar well-defined item
- *Programmatics*, consisting of initial and full operational capability (FOC) need dates, acquisition strategy assumptions, overall system-of-system integration schedule dependencies, etc.
- *Unique cost drivers* not defined above that most likely will have a significant impact on the costs estimated

To arrive at costs, acquisition strategy options were used to derive discount factors relative to historical program costs generated from more traditionally based CERs or analogous programs.

Further details of space- and ground-based asset cost model-specific inputs are summarized in Section 2.3, ACEIT Model.

The objective of the cost analysis provided for this study was to strive for both completeness and consistency. All systems defined both in the baseline and in the options were subdivided into acquisition phases where appropriate. This ranged from pre-engineering and manufacturing development (EMD) advanced technology demonstrations (ATDs) to concept definition and program definition risk reduction or demonstration through EMD and production. It continues through sustained operations, support, and replacement modifications at least through FOC and through FY 20. All costs include both contractor and government system program office (SPO) and support costs required to implement, operate, and maintain the systems.

This common cutoff time frame through FY 20 provides the same time-phased and cumulative life-cycle cost (LCC) basis for all systems. A complete cost breakdown structure (CBS) used for all estimates in this study along with a sample output can be found in the Tecolote contractor report.[1]

Finally, besides a consistent time frame, all estimates beginning with the baseline reside in a common cost analysis shell, ACEIT (described in the next section). ACEIT provides a consistent set of formatted outputs, analogous program cost databases, and applicable CERs based on cost to cost or on non-cost to cost. This tailors the process so that the best tool within the tool kit is used to generate the estimates with the best fidelity possible, given the data provided. All inputs can be self-documented, citing the originator, the rationale, and other pertinent details. (A description of the summary-level cost analysis assumptions is provided.)

A risk assessment at the architecture level for each option was performed to quantify the aggregate amount of cost uncertainty. This arises from the estimating technique and is based on the hardware, software, and system technical maturity levels as well as the extent to which the system can be produced, operated, and supported. The methodology was linked to the ACEIT model by applying a readiness matrix in an attempt to adjust “most likely” cost estimates to account for historical cost growth of programs assessed with overall moderate to high program risk. The matrix provides a standard approach to assessing the maturity levels of the system’s hardware and software to meet system performance and the capability of being produced, operated, and supported in the intended space environment. Because of the limited data and the level of fidelity, only a cursory risk assessment cross-check was made on two of the three new programs estimated.

2.3 ACEIT Model

To estimate the cost of proposed new systems, Tecolote developed a summary-level cost-estimating tool for satellite constellations and implemented that methodology in an automated calculation tool. The purpose of this tool is to estimate the cost of a satellite constellation over its life cycle while assisting the user in providing a minimum description of the system. Furthermore, the panel was required to project costs as far as 20 years—beyond the like applicability of traditional CERs, according to historical data. Satisfying this purpose required the selection of top-level methodologies that are described in the contractor report.

The acquisition reform regulations promulgated in the early 1990s mandated the adoption of a standard CBS. Specifically, DoD 5000.4 mandates the use of a MIL-STD-881 CBS for satellite systems. Because the estimates generated for the SAB will not be subject to formal review or approval, it was not necessary to follow the letter of this standard. However, the MIL-STD-881 CBS was used as a starting point. Owing to the summary nature of the technical information we believed would be available on the systems to be estimated, this CBS was trimmed to only 35 estimated items. Of these, several items are estimated with the same methodology and differ only in the acquisition phase in which the costs occur. (A list of

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[1] Tecolote Research, Inc., *Air Force Scientific Advisory Board 1998 Summer Study, Cost Estimating Report,* Contract Report CR-0957, 1998.

the CBS items is in Table J-1.) The contractor report discusses each of the estimated CBS items in detail. We will not bother to describe the levels of summation here, other than to say that the highest levels are by program acquisition phase—pre-EMD, EMD, production, and operations and support—and the costs for these generally occur in that order over time.

2.4 Risk Methodology

The development of the risk assessment for this study has origins from the National Aeronautics and Space Administration (NASA) taxonomy, which relates technological maturity to potential cost growth. This NASA risk assessment taxonomy is extracted from a briefing given by the Goddard Space Flight Center in 1988. Table J-2 shows that taxonomy, defining technology readiness levels (TRLs) according to the maturity of the technology.

Each TRL and associated relative risk level also relate to historical program trends in cost growth. The lower the TRL, the higher the risk and the greater the potential (or percentage) for cost growth over cost reductions. The higher the TRL, the lower the risk and the more likely that a symmetrical or equal probability of cost reductions and growth could occur.

Again, limited data and fidelity limited the extent to which this methodology could be applied to cost estimates. Only a cursory risk assessment cross-check was made on two of the three new programs estimated. The ACEIT model cost estimates for the AOV program accounted for a sufficient level of program risk when compared with the NASA shuttle program as historical reusable space assets after normalizing the data for economic and technical maturity differences. The STARLITE SBR program estimate also compared favorably with the Discoverer II program LCC estimates, given the acquisition stage and the technology maturity level of active array element components as one of the major satellite system cost drivers.

For this study, the risk category has been expanded beyond TRLs to cover all phases of the LCC. Expanded risk categories are displayed in Table J-3. The matrix expands the definitions to several categories to more readily qualify the associated risk.

Because of the advanced concepts nature of the architecture-level systems being defined and the quick cost analysis turnaround required, it was determined that the risk assessment reporting process required streamlining. For this study, the risk matrix was further reduced to five categories.

Software development was added as a separate risk category to reflect not only the technical feasibility during hardware development (as it was originally intended) but also the extent of software maturity at the start of the RDT&E program and the ease of producing and integrating the combined hardware and software components into the system leading to deployment. Software maturity is based on the extent of new design, coding, and testing required, and spans descriptions all the way from commercial off-the-shelf (COTS) software, to reusable software, to rehosting of software on a new processor, to slight modifications of existing code, to a new development effort.

Besides the RDT&E activity, ease of production or producibility is another risk category that refers to the transition from development that is required to design new tooling, manufacturing processes, and techniques. This allows the transition from building a unit in a lab environment with small quantities to a manufacturing environment with larger quantities.

Table J-1. *Generic Spacecraft Cost Model Cost Breakdown Structure*

Space System
Pre-EMD Phase
EMD Phase
Prime Mission Equipment
Launch Vehicle Subsystem
Launch Vehicle
Launch Integration
Space Vehicle Subsystem
Space Vehicle Prime Mission Equipment (PME)
Space Vehicle Integration, Assembly, and Test (IA&T)
Space Vehicle Software (Development Only)
Payload
Communications & Digital Electronic
Spacecraft Bus
Shroud (Payload Fairing) & Adaptor
Space Vehicle Program Level
Aerospace Ground Equipment
Ground Subsystem
Ground System Integration
Ground System Software
Ground System Mission Equipment
Ground System Operations Equipment
Systems Engineering Program Management
Development Fee
Other Government Costs (SPO Only)
Continuing Development

Table J-1. *Generic Spacecraft Cost Model Cost Breakdown Structure (continued)*

Production Phase
Prime Mission Equipment
Launch Vehicle Subsystem
Launch Vehicle
Launch Integration
Space Vehicle Subsystem
Space Vehicle PME
Space Vehicle IA&T
Payload
Communications & Digital Electronics
Spacecraft Bus
Shroud (Payload Fairing)
Space Vehicle Program Level
Ground User Equipment
Production Fee
Other Government Costs (SPO Only)
Operations & Support Phase
Personnel
Mission Personnel
Operations Personnel
Equipment Maintenance
Mission Equipment Maintenance
Operations Equipment Maintenance
Other Government Costs (SPO Only)

Table J-2. *Technology Readiness Levels From NASA*

TRL	***Definitions***	***Relative Risk Level***
1	Basic principles observed	High
2	Conceptual design formulated	High
3	Conceptual design tested analytically in relevant environment	Moderate
4	Critical function/characteristic demonstrated	Moderate
5	Component or breadboard tested in relevant environment	Moderate
6	Prototype/engineering model tested in relevant environment	Low
7	Engineering model tested in space	Low
8	Full operational capability	Low

Table J-3. *Expanded Risk Assessment Matrix*

Risk	***Low***				***High***
Category	***1***	***2***	***3***	***4***	***5***
Performance	In Use	Prototype Exists	Development	Design	Concept
Operability	Operational Tests Complete	Operational Concept Demonstrated	Design Baseline Established	Requirements Established	Operational Concept Defined
Producibility	Established	Demonstrated	Feasible	Not Demonstrated	No Known Production Experience
Supportability	Established	Demonstrated	Design Incorporated	Requirements Established	Concept Defined
Affordability	Extremely Confident	Very Confident	Confident	Fairly Confident	Slightly Confident
Schedule	Extremely Confident	Very Confident	Confident	Fairly Confident	Slightly Confident

Since the estimates also include the cost associated with operating and supporting the system after deployment, we included this risk category to bound the cost growth and uncertainty levels associated with O&M and MILPERS budgetary cost projections. Finally, schedule was kept as a risk category to reflect the likelihood of being able to meet the RDT&E and production schedule.

The modified risk assessment data sheet for this study, with explanations, is displayed in Table J-4. Risk levels were reduced from five to three to reflect the limited resources available in this study to adequately quantify risk.

The risk ratings across the five risk categories are summarized by applying the risk ranking number for each category to a cost distribution against the ACEIT model–generated “most likely” estimate. Depending upon the risk category, the upper-bound estimate relates to associated historical program trends in cost growth. The higher the risk, the greater the potential (or percentage) for cost growth over cost reductions. Conversely, the lower the risk, the more likely that a symmetrical or equal probability of cost reductions and growth could occur.

Table J-4. *Risk Assessment Explanations*

Risk Category	*Low (1)*	*Moderate (2)*	*High (3)*
Hardware/ System RDT&E Performance (3600) Reflects technical maturity or readiness levels	**In Use/COTS/Prototype Exists** Best Case: Existing or easily adaptable technology. Minimal changes before it can be integrated. Worst Case: Performance demonstrated in lab.	**Breadboards Exist/ Lab Developed** Best Case: Components under development or in test and evaluation (T&E) process. Brassboards and breadboards exist. Worst Case: Development limited to engineering studies, with little if any lab testing. Major integration issues must be addressed.	**Conceptual** Item at earliest stage of definition. Many unresolved technical issues remain to be addressed. Integration issues not addressed.
Software Development RDT&E (3600) Extent of reuse, complexity and modularity, etc.	**Established/ Reusable Code Available** Best Case: Proven significant reusable software. Slight change in existing software. Worst Case: Equivalent software in another language or significant reusable code has been used previously.	**Major Changes/ Similar Software Exists** Best Case: Major changes in existing software, up to 50 percent new code. Worst Case: New software required may be similar to other programs. Prototypes and simulations used in an engineering hardware environment.	**No Software Code Exists** New software required that may be pushing state of the art. Deliverable code not produced.
Producibility (3020/3080/etc.)	**Established/ Demonstrated** Best Case: Item in production or has been successfully produced before. No retooling or additional manufacturing processes required. Worst Case: Similar item in production or has been successfully produced before. Simple retooling and only minor capital investments required.	**Similar Item or Lab Units Produced** Best Case: Similar item not produced in quantity and may require significant changes, retooling, and capital investments. Worst Case: Production limited to the lab with only low-yield results. Producibility assessment required before major crew retooling and capital investments can begin.	**No Known Production Experience** Production experience limited to research and development (R&D) applications. Materials and production processes not well defined.
Acquisition Schedule (RDT&E + Production)	**Very Confident** Best Case: Schedule estimate based on well-defined item with no hardware or software changes required. Worst Case: Schedule extrapolated from program actuals for a similar item with a minor increase in hardware or software complexity that is already in production.	**Confident** Best Case: Results computed within range of estimating relationships or very close to analogous system with a moderate increase in complexity. Worst Case: Results computed outside range of estimating relationships or poorly defined analogous system with a significant increase in complexity.	**Slightly Confident** Major uncertainties exist on item scope and definition and highly complex hardware or software.

Table J-4. *Risk Assessment Explanations (continued)*

Operability & Supportability (3600 & MILPERS)	**Operations & Maintenance Tests Completed; Support Demonstrated & Established** Best Case: Item has successfully completed T&E to user's satisfaction. Support procedures in place. Worst Case: T&E not yet completed. Design exposed to simulations, but not actual mission conditions. A similar item was fielded and supported or demonstrated to be supportable during field testing.	**Operational Requirements Established & Similar Item Fielded** Best Case: Design baseline defined and operational requirements established to satisfaction of "user." Similar item with substantial modifications has been fielded. Worst Case: Operational requirements established, but not proven. Similar item with substantial modifications under development, but not fielded.	**Operational & Support Concept Defined or Partially Proven & No Similar Item Fielded** Operational concept only partially proven or not proven at all and there is limited past operational experience to base future on. No similar item has been fielded or developed, and all existing support procedures are inadequate to base future on.

2.5 Default Conditions and Assumptions

Cost estimating is just that, estimating. Any predictive estimate requires a number of assumptions. Also, default conditions must be established to cover situations where accurate input is not available. In this study, with the aid of contractor support from Tecolote and input from other SAB panels, we made the necessary assumptions and established default positions appropriate for this study. Assumptions and default positions are the best obtainable conditions considering the availability of planning data after 2003 and the timelines of this study.

2.5.1 Default Conditions

The Cost and Acquisition Panel used the FY 99 PB as a starting point for both programs and costs. The PB was supplemented by data from the FY 00 Program Objective Memorandum (POM) to obtain data on existing programs up to FY 04–05. Various planning documents and projections, such as the Defense Planning Program, were used to project potential funds requirements for FY 06–20. Absent firm knowledge that a program was to undergo major changes, we straight-lined the funding for the program, with a 2.2 percent inflation rate. There were exceptions to this logic. SAF/AQS[2] personnel (Cost Panel members), having interacted with many of the space Program Element Monitors (PEMs), were aware of specific program schedule and budget issues captured in the outyears of the PEM, yet not captured in the PB. In those cases, the budgets were adjusted (in every case downward) in FY 04 and FY 05 before being escalated at 2.2 percent into the future.

There was a consensus on the Cost Panel that the cost of space systems are declining and that CERs that are based upon historical space systems costs will overestimate the cost of future programs. There are several sound arguments for this position but little supporting data. The first of these arguments is that the commercial space business is rapidly expanding, bringing with this expansion the deflationary pressures of competition and a large base over which to amortize fixed costs. Second, the space industry is maturing. What was once a laboratory-type effort requiring the skills of a handful of highly educated specialists has become increasingly industrialized, allowing for mass production (as in the case of Iridium). Third, technology advances have increased the availability and reduced the price of the components once unique to specific satellites. In some cases, such as gallium arsenide monolithic microwave integrated circuits, these components have become common in consumer electronics (cellular phones, for example). This increased availability has meant that many satellite components, and even satellite buses themselves, can be purchased off the shelf rather than suffering the cost and delay of

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[2] Assistant Secretary of the Air Force, Acquisition, Space and Nuclear Deterrence.

development. Last, acquisition reforms should allow the Air Force to leverage these cost savings in procuring militarily useful capability, either through buying commercial services or military-specific satellites.

We needed to be able to model the consensus cost decrease. It seems implausible to us that this trend could continue indefinitely or that it could apply universally to all space systems. However, it does seem likely, for the reasons listed in the previous paragraph, that costs are declining, and it is convenient to model these reductions as a percentage reduction per year in real terms. It became a question of what the percentage reduction per year is and how to apply it.

The only way to correctly demonstrate and quantify these reductions is to collect data. There simply was no time to undertake such an effort on this task, and our experience has been that commercial vendors have been reluctant to provide such cost data to the Government for proprietary and competitive reasons. In the interim, we determined the average cost per pound of various general types of satellite hardware. We did the same for ground and space software on the basis of cost per source line of code. This number for spacecraft buses and communications equipment was derived from the Unmanned Spacecraft Cost Model Version 7. The time center of this data is about 1992 and reductions were calculated from this date. We considered the cost reductions in light of the historical progress to date on lowering satellite costs.

The most aggressive cost reduction factor we could justify to ourselves was 6 percent. Furthermore, we believe that this factor can only be applied to classes of hardware experiencing the most commercialization: communications payloads and spacecraft buses. We believe that this factor also may apply to software, given the proliferation of modern software development practices and tools. However, for hardware with little or no commercial interest, it is hard to see how any of the factors leading to cost reduction apply other than piece parts that are common with commercial satellites. So, for missile warning satellites, little if any reduction would be seen in cost. Table J-5 lists the cost reduction factors in the model, calculated from 1992 to the first year of production, when the major decisions that could reduce costs have nearly all been made.

An important weakness of this model is that it assumes that the year of technology for weight estimates that feed it is 1992. However, there is legitimate expectation that ever more capability can be achieved from every pound of spacecraft. If the weight estimates are not properly calibrated, the model will predict poorly and unevenly. It will most likely underestimate future costs as more capability is packed into every pound estimated, leading to weight estimates calibrated below what 1992 technology would allow. The only rigorous way to avoid this problem is to develop and enforce a standard set of design rules for estimating weight that would be used across systems estimated with this model. However, the same can be said about the application of any weight-based CERs to estimate future system costs. Such applications must always be a matter for review and intense scrutiny to prevent CERs from being misapplied due to overly optimistic technical inputs.

Table J-5. *Annual Percentage Reduction of Payload Cost Since 1992*

Mission Types	***Reduction Per Year***
Communications	6%
Navigation	2%
Weather	2%
Synthetic-Aperture Radar Imaging	3%
Electro-Optical Imaging	4%
Missile Warning	1%

2.5.2 Assumptions

In many cases, when presented with new systems from another panel, we used historical data and the system assumptions made by that panel to arrive at a cost for the system. For example, when costing out a new satellite system, we used existing data on current constellations and added the necessary new features to come up with a price. This procedure, although not exact, fit our purposes of doing a rough comparison of options for the future.

Enumerated assumptions applied to ACEIT are as follows:

- The recurring costs of payloads, buses, and wideband communications are based on dollars per pound. These three items (dry weight) represent the space vehicle hardware costs.
- The nonrecurring cost of hardware is based on a factor of recurring costs, dependent on a “design legacy” choice of high, medium, or low. A low–design legacy system represents a “clean sheet” design. A medium-legacy system has significant similarities to previous programs, using mature technologies, and primarily uses off-the-shelf components. A high-legacy system involves a minor modification or upgrade to a previous program.
- Prototype vehicles are assumed only for low– and medium–design legacy systems. For high legacy, there is simply no need for a prototype, and the initial vehicle counts against constellation size.
- The recurring cost per pound for payload varies by payload type. These costs per pound are drawn from historical programs. The highest cost per pound is $190,000 for missile warning. The next highest is $170,000 per pound for electro-optical imaging payloads.
- Required constellation size and mean mission duration dictate the number of on-orbit spares required. These inputs drive the number of satellites produced and launched during a program’s life cycle.
- Phased costs are based on dates of initial/final operational capability, end of mission date, duration of program development phases, and time required to produce a satellite.
- The launch vehicle for a constellation is based on orbit altitude, inclination, and payload weight.
- All dollars are then year and assume a 2.2 percent per year inflation rate.

Another important assumption that the panel made was that the Total Obligation Authority (TOA) of the Air Force would increase only because of the inflation rate. We did not assume that the Air Force budget would increase due to external events in the world or internal decisions in DoD.

System LCC was based on a hierarchical construct that considered flyaway, weapon system, procurement, program acquisition, operation and support, and disposal costs, as Figure J-1 illustrates.

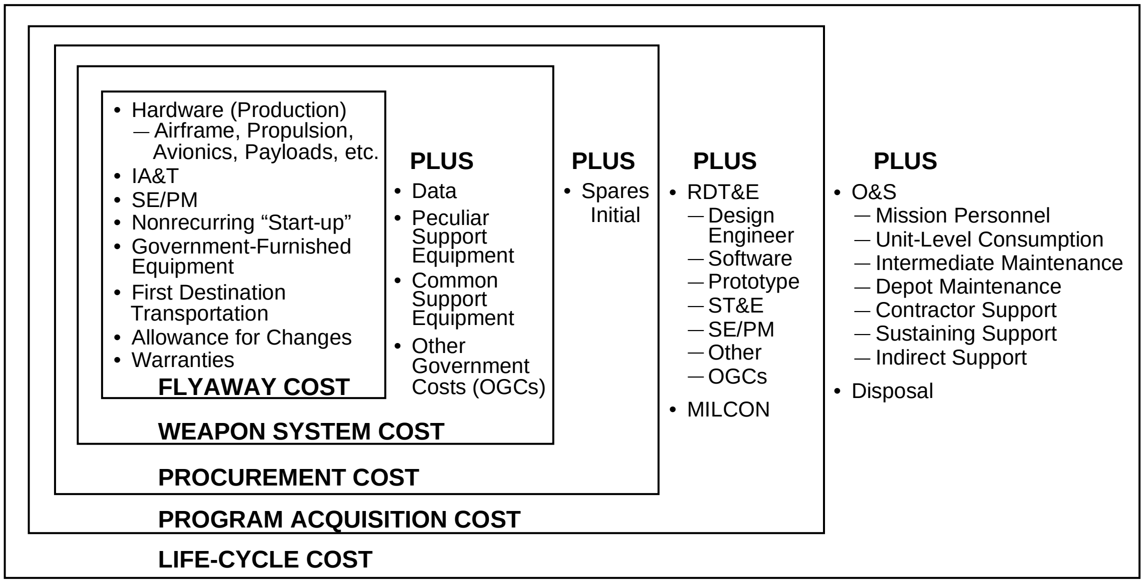

Figure J-1. *LCC Composition*

3.0 Cost Data

3.1 Introduction

Using the ACEIT model and the above assumptions, the following cost estimates were generated. For each option estimated, costs of infrastructure, environmental elements, launch, ISR/warning, space control, navigation, and infostructure are indicated separately, but add up to a total system cost each fiscal year. Total mission area costs cover the next 20 years. Figure J-2 represents the costs of each option in terms relative to the baseline.

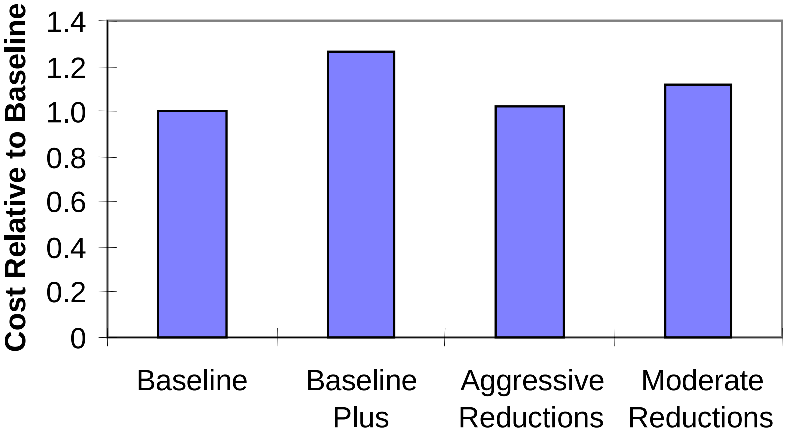

Figure J-2. *Relative Costs of Options*

Another major task for the Cost Panel was to project the unclassified Air Force space and ISR aircraft budget into the future, considering the cost of proposed new systems and possible savings. The purpose of this exercise was to quantify budget constraints on future plans, constraints that were qualitatively understood as meaning no real increase in budget authority. As a point of departure, we created a Microsoft Excel spreadsheet of the 14 January 1998 PB for space program elements (PEs) and ISR aircraft programs out to 2003. The aircraft (Joint Surveillance, Target, and Attack Radar System, Airborne Warning and Control System, U-2, and various unmanned aerial vehicles [UAVs]) were included because of the desire to consider missions and architectures across the systems that accomplished them. Details can be found in the contractor report. Beyond 2003, the budgets were essentially flatlined, assuming a constant 2.2 percent inflation rate of then-year dollars. This baseline was maintained as a separate worksheet and mapped into all subsequent options. There were several large PEs that were not flatlined from 2003 because of known reductions and terminations of activities. Among these were Milstar, evolved expendable launch vehicle (EELV), and Gapfiller. We also added a budget line to the baseline in Infostructure for terrestrial-based communications (landlines). This roughly $60-million-a-year estimate came from a study done for the Office of the Space Architect.

The initial hope of developing a family of alternative architectures was made futile by the time limitations on the study. The architectures gave way to a set of options sketched out by the panels. While as many as five options were initially considered, by the end of the study only three options were presented and just one recommended. The first of these options (baseline plus) was the baseline as described above plus the three future systems—SBR, GBR, and AOV. Given budget constraints, clearly that option is not affordable. The second option (aggressive reductions) included the above new systems, but severely reduced operating costs by relying almost exclusively on commercial communications, and rapidly terminating or transferring a large number of current activities including military satellite communications (MILSATCOM), launch, and range support; this option too was rejected. The third option (moderate reductions) was to dramatically reduce operating costs, while transferring the majority of responsibility for communications and range activities to commercial entities. The following paragraphs describe these three options.

3.2 Baseline

Each option used the 14 January 1998 PB as a starting point. We would have preferred to use the POM, because the PB goes only to 2003, whereas the POM goes to 2005. We extended the budget beyond 2003 in most cases by applying a 2.2 percent inflation factor each year until 2020, the agreed-to end date for our financial analysis. There were exceptions to this logic. SAF/AQS personnel (Cost Panel members), having interacted with many of the space PEMs, were aware of specific program schedule and budget issues captured in the outyears of the POM, yet not captured in the PB. In those cases, the budgets were adjusted (in every case downward) in 2004 and 2005 before being escalated at 2.2 percent into the future. Those reductions are the source of the slight dip in 2004 and 2005 before the smooth increase in the budget due to inflation. Specifically, MILSATCOM, Ultra-High Frequency Follow-On, and EELV were decreased in line with POM projection. This baseline is shown in Figure J-3. The trend toward increasing outyear costs is solely due to inflation.

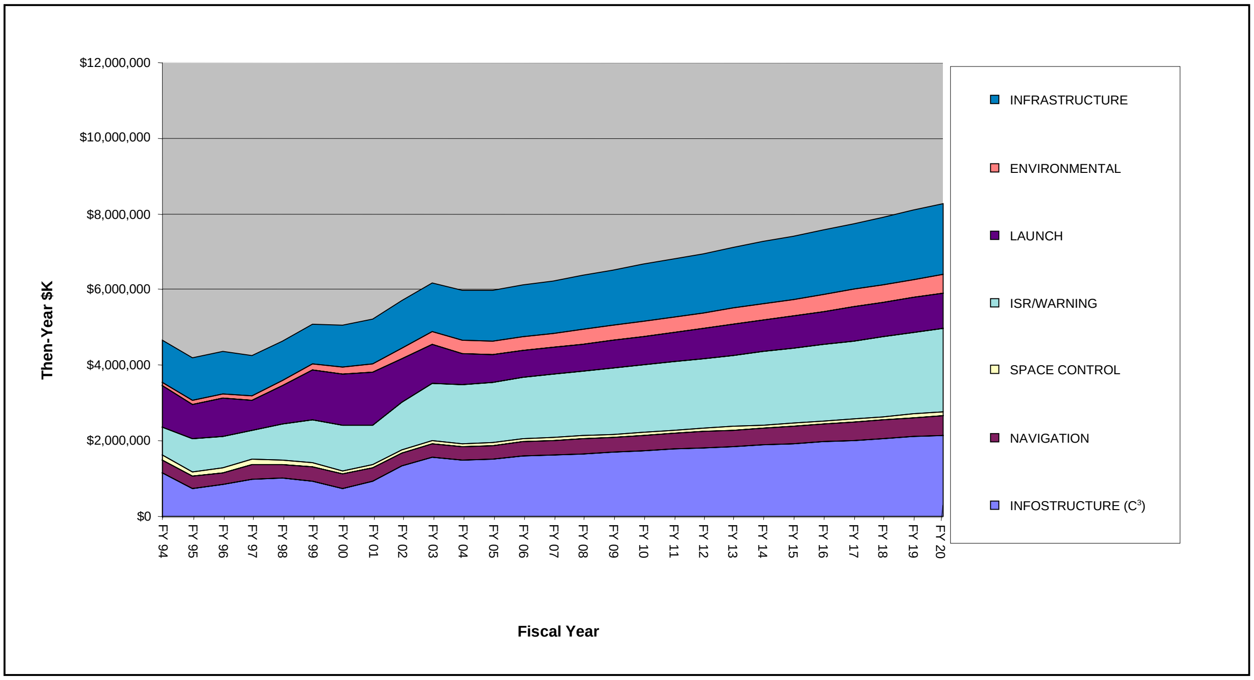

Figure J-3. *Budget Baseline*

3.3 Baseline Plus

The first option, referred to during the study as baseline plus (Figure J-4), included the three new systems: a GBL, an SBR, and an AOV. The systems are described in previous appendices. The reader should be cautioned that these are order-of-magnitude estimates and are not suitable for traditional budget planning. After a decision to delay the AOV, the schedule for these systems occurred in order, with the systems following each other by approximately 5 years. At the request of the study director, the annual funding levels for these systems are aggregated into one account described as “new programs” in the study findings (Figure J-4). The sum of these new programs quickly grows to more than 2.6 billion then-year dollars per year by 2006 and averages $2 billion from FY 01 to FY 20, for a 20-year total of $41 billion, peaking at $3 billion in FY 15. These new programs would require the portion of the budget considered to expand by roughly 5 percent each year from FY 00 to FY 06. The Cost Panel believed that this was unrealistic; therefore, only options including one or two of the new programs and substantial reductions of other budget lines could be seriously recommended. For example, including only the SBR requires the budget under consideration to be increased by $16.7 billion or 8 percent on average over 20 years, with a peak of $1.7 billion in FY 07.

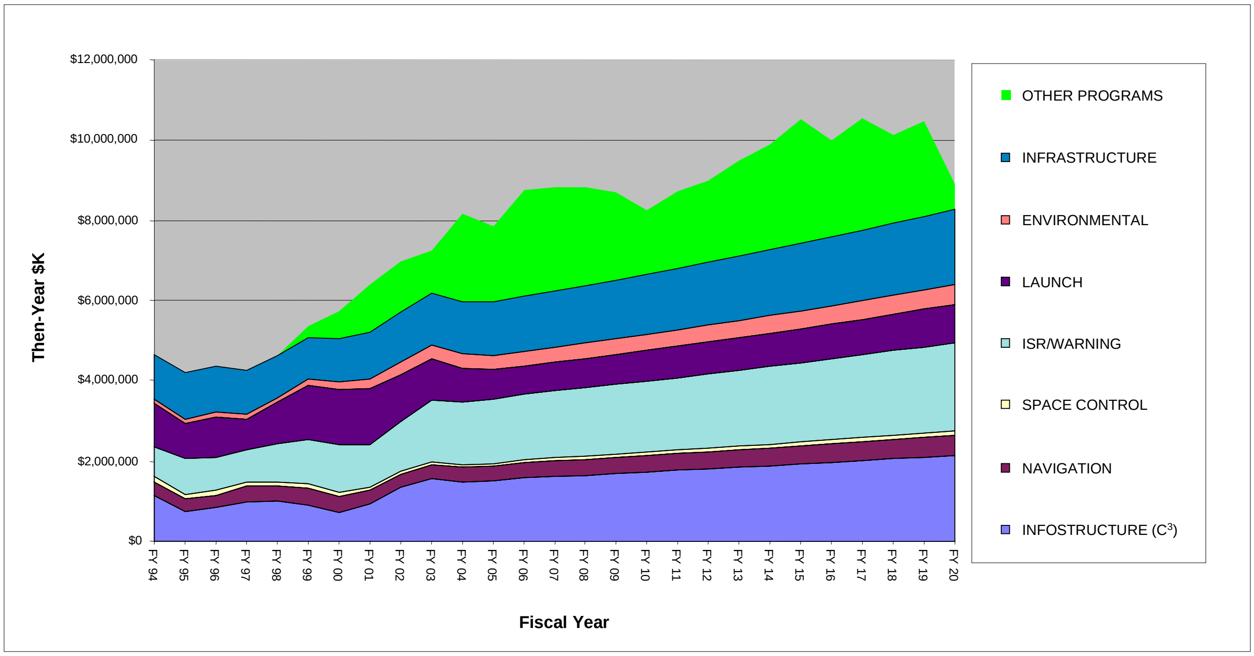

Figure J-4. *Baseline Plus New Programs*

3.4 Aggressive Reductions

Much of the effort of the Cost Panel centered around identifying savings that could be achieved by more efficiently acquiring, launching, and operating systems. There was also serious consideration of transferring and eliminating certain activities not central to the mission of an aerospace force, calling such reductions “divestiture.” The remaining two options took different approaches to quantifying potential savings.

The aggressive reductions option (Figure J-5) promulgated by the Operations Panel started with the baseline-plus option and reduced, eliminated, or transferred responsibility for all activities not central to warfighting from space. Shown as Force/Mission/Efficiency, the substantial savings off of the baseline begin as early as FY 01 and quickly reach $2 billion per year in FY 04. Between FY 01 and FY 20, total savings exceed $45 billion, averaging $2.3 billion per year.

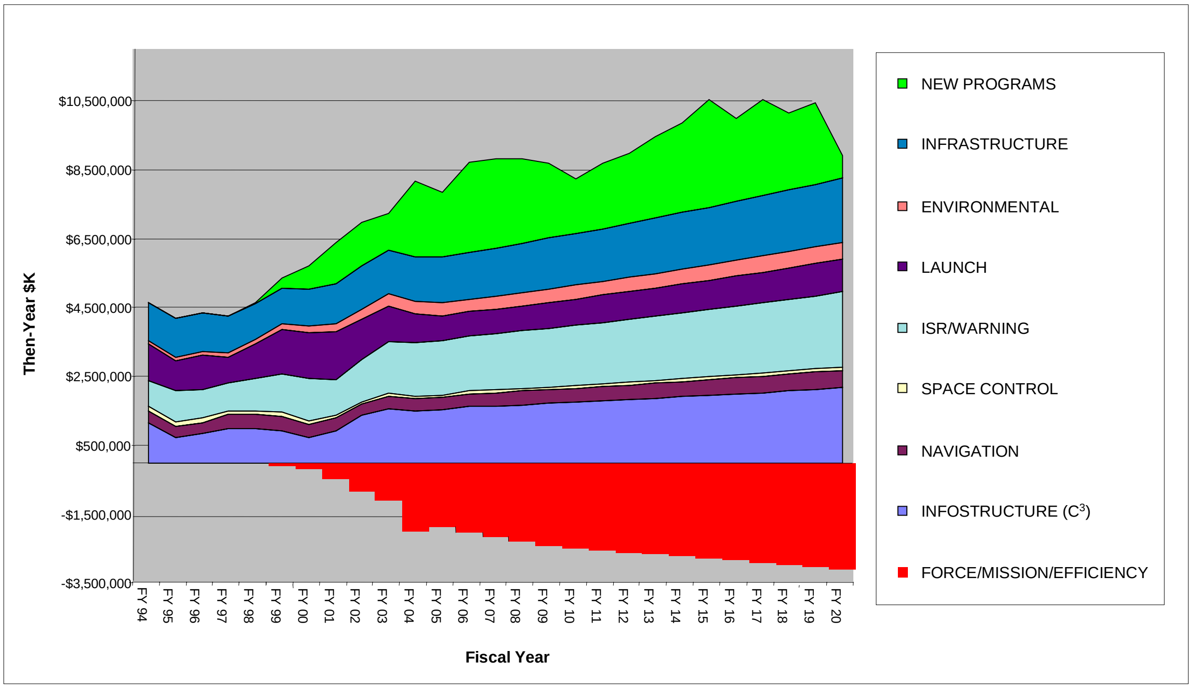

Figure J-5. *Aggressive Reductions Because of Force and Mission Reductions and Efficiencies*

Everyone was well aware of the political and management challenges of making such draconian reductions, especially in the near future and where the Air Force has commitments to the other branches of the armed services. For example, there are hundreds of millions of dollars invested in Milstar terminals deployed throughout the military. Any reduction or elimination of Milstar service would require additional investments to continue to provide equivalent capability. Furthermore, it is not certain that another government agency or commercial entity would be interested in accepting the transfer of missions, assets, and requirements. An example of this is the launch operations of the Eastern and Western Space and Missile Centers. In effect, the Air Force subsidizes commercial and civil launches from these facilities by charging only the marginal cost of additional launches. The full cost of operating these facilities, evenly allocated to all users, would be many times what is currently charged and prohibitively expensive for many users. It is difficult to envision a commercial scenario that would be profitable without similar subsidies through other channels that might not be as politically compelling as military access to space. The “aggressive reductions” option was therefore presented as an ideal that could be reached for but not be implemented.

3.5 Moderate Reductions

The “moderate reductions” option (Figure J-6) was an attempt by the Cost Panel to identify aggressive but realistic reductions in a limited number of areas. The three areas targeted were communications, operations and support (including MILPERS), and range operations. In communications, almost all programs are phased out except a portion of the MILSATCOM budget preserved in good faith to current users. Some of this cost is put back in a wedge for commercial leased communications. All O&M and MILPERS costs were reduced 30 percent, decreasing by 10 percent per year starting in FY 01. By FY 03, this amounts to a savings of over 360 million then-year dollars, and averages 5 percent of the budget in subsequent years. These savings were designed to reflect general process improvement and consolidation of support functions. Finally, the O&M and MILPERS costs associated with the ranges are reduced to just 20 percent of their baseline values by FY 03, and all investment is eliminated, reflecting a transition to a “National Range” approach for launch infrastructure. Each of these reductions must be studied thoroughly to assess its feasibility. From FY 01 to FY 20, savings from these reductions in range costs average just over 3 percent of the baseline budget being considered.

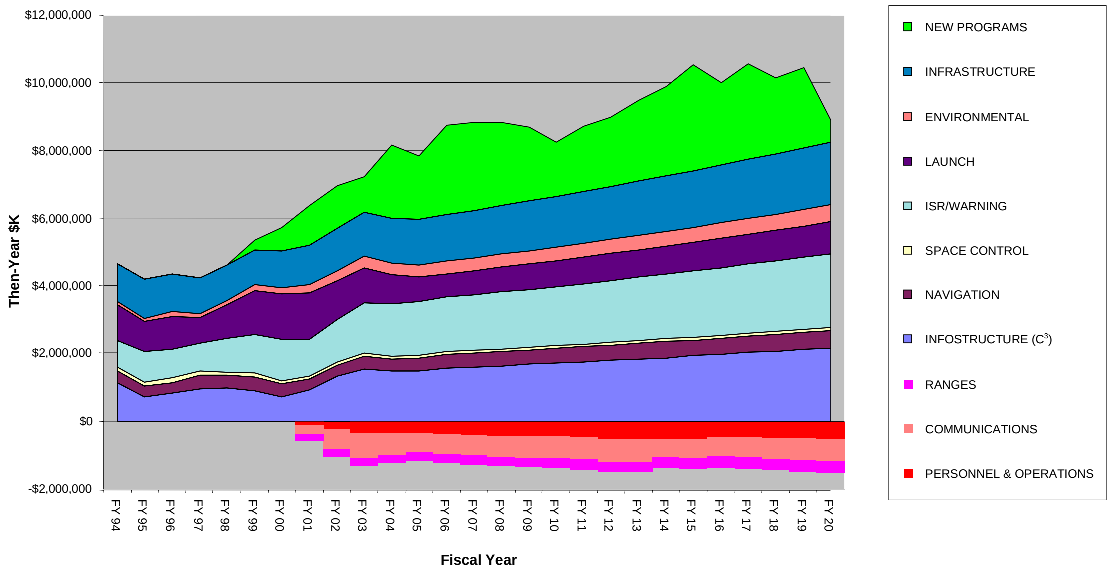

Figure J-6. *"Moderate Reductions" to O&M and MILPERS Accounts, Communications, and Ranges*

The savings from the "moderate reductions" option are sufficient to offset only two-thirds of the increases required by the "new programs" estimated. For example, the then-year cost of the SBR program is $16.7 billion from FY 01 through FY 20. Savings in the "moderate reductions" option total more than $27 billion over a similar time frame. Therefore, the "moderate reductions" option is consistent with the objectives and recommendations of the Summer Study.

4.0 Cost Panel Recommendations

On the basis of the results from Section 3.0, we recommend that the process initiated here in the Summer Study be augmented as described below and institutionalized in the Air Force Planning Process. The process described in this section to derive cost estimates at the "Option" level can and should be routinely used in combination with Measures-of-Effectiveness estimates (such as that described previously) in the Air Force Modernization Planning Process. While we have focused on the cost term in the denominator of the overall benefit/cost ratio, the ratio is the key parameter in any prioritization among options. The Air Force planners tend to use benefit/cost ratios, but only at the system or component level. Current usage results in suboptimization without that benefit/cost consideration at the architecture level.

The complete space-related system-of-systems can and should be planned to achieve a synergistic optimum, which may provide solutions that appear wrong at the system or component level. In fact, the process described in this Summer Study is not as rigorous as that which should be used by the Air Force. Methods are available that can seek and find system-of-systems optimums, and many of those can handle uncertainty and deal properly with constraints, such as needing a minimum level of performance in one area at "any price" (OPR: AF/XO, AF/XP).

5.0 Acquisition Findings

The results of Section 3.0 point out the difficulty of funding the baseline under current TOA levels. In FY 99, the Air Force investment (procurement, R&D funds) budget for space is $4.25 billion, or about 13.8 percent of the Air Force's total investment budget.[3] Historical budget data and projections indicate that these levels are consistent from FY 93 through FY 03. It is not possible to implement the findings of this study without an appreciable TOA increase. However, one should reasonably expect that there will this total or percentage will not change significantly. Given that the assumptions used in the model are based on historical data, the only way mission needs can be met is to challenge our way of doing business in space acquisition. In this section, we investigate some cost drivers and offer findings that may be addressed as cost-cutting measures to help the Air Force afford the future.

The first assumption to be challenged is that TOA will remain constant. The panel held no illusions that the space portion of TOA will be substantially increased. However, if the Air Force shifts its focus from "air" to "aerospace," efficiencies will ensue from close cooperation and incorporation of space needs into aerospace doctrine.

5.1 Consider Commercial Systems to Meet Military Needs: Lease versus Buy versus Fee for Service

Current and planned commercial space systems, most notably communications systems, offer capabilities that suit the military's needs. These systems could enhance current DoD capabilities and augment or replace planned systems. A partnership with industry avoids the up-front costs of development and acquisition, although there is risk in becoming dependent on a single commercial system. This approach has the added advantage of avoiding large up-front development costs. System costs can be spread more evenly over the program life cycle, simplifying the planning process and avoiding becoming a "target" for cost cutting.

Not all Air Force needs can be met with commercial capabilities. There are mission-critical military requirements that dictate dedicated military-unique capabilities. For example, high-priority, nuclear-survivable, assured communications to transmit Emergency Action Message traffic are not likely to be entrusted to commercial communications circuits alone. However, commercial services could be used for the vast majority of Air Force communications.

Both leasing and buying offer advantages to the military. Currently, leasing transponders is more expensive over the equipment's life cycle than buying if requirements are large. Nonetheless, leasing offers some distinct advantages: no up-front development or purchase costs, short-term use and ability to grow if needs are not stable or predictable, as well as state-of-the-art service. Where requirements don't support the need for an entire transponder capacity, contracting on a fee-for-service basis (paying for the time used) or a "lease back to industry" option could offer a solution for non-essential communications at minimal cost.

Leasing's disadvantages include a possible absence of backward compatibility (that is, handsets and terminals could one day be outmoded, forcing upgrade of ground and aircraft equipment). Furthermore, leasing may not offer all the features that are desirable or required. Finally, leasing is more costly than buying over the program's life cycle (the long term). However, this cost analysis needs to be updated as technology and marketplace growth continue to drive costs down. For example, the price of a telephone call from New York to London dropped from $234.70 in 1930 to $32.33 in 1970 and is $1.17 today, a total reduction of 99.5 percent. With Iridium and other communications systems being fielded in the next few years, competition may make leasing the more attractive alternative.

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[3] Scott Orton, ANSER, Assistant Secretary of the Air Force, Acquisition, Space and Nuclear Deterrence, Plans and Policy (SAF/AQSP), personal communication, 25 September 1998.

In summary, the military will continue to buy systems to satisfy military-unique requirements. For other needs, the military must analyze the tradeoffs of leasing and buying.

5.1.1 Commercial Acquisition Requirements

DoD 5000.2-R, Section 3.3.2, Paragraph e, requires that commercial capabilities "... be considered as the primary source of supply" (10 USC 2377; Clinger-Cohen Act of 1996, 5201, Procurement Procedures) to meet requirements before new systems are proposed. We must ensure that this requirement is enforced.

There appears to be no central office within DoD maintaining an up-to-date library of commercial capabilities or services (available or planned). As a result, the process used to assess commercial capabilities for meeting Air Force needs is extremely difficult to carry out and subject to considerable errors and omissions. Air Force officials in different locations have no central storehouse of information on available capabilities. Conversely, industry officials have no single DoD focal point to describe current and planned capabilities of commercial satellites.

5.2 Piggybacking

As commercial systems proliferate, the possibilities may be greater for piggybacking payloads. There may be cost-effective alternatives for placing commercial payloads on military satellites. Conversely, investigation may show that placing military payloads on commercial satellites makes sense. There is no office with the responsibility to encourage such piggybacking options.

5.3 Partnering With Other Agencies and With Industry

In many cases, partnering with government agencies and industry offers several advantages, such as reduced costs and consolidation of redundant efforts. The Air Force has entered partnerships with the National Reconnaissance Office (NRO), NASA, the Defense Advanced Research Projects Agency (DARPA), the Department of Commerce (DoC), and the Department of Transportation (DoT). The National Polar-Orbiting Environmental Satellite System (NPOESS) merges DoC (Polar-Orbiting Environmental Satellite) and Air Force (Defense Meteorological Support Program [DMSP]) satellite programs, and will provide enhanced capabilities while saving the Government $1.7 billion over the life of the program. The NPOESS program is particularly notable because of its international partnership with a European meteorological satellite. DMSP consolidation, the first phase of NPOESS, has transferred 255 Air Force active-duty billets to other Air Force programs.

The Global Positioning System (Air Force/DoT) has progressed from being a unique capability to become a civil and military necessity. The Discoverer II program (Air Force/NRO/DARPA) will develop and demonstrate technology for a SBR system capable of executing a global ground moving-target indicator mission.

The Air Force Research Laboratory's (AFRL) science and technology activities afford unique opportunities for partnership, using Cooperative Research and Development Agreements (CRDAs), Alliance Agreements with Industry, Technology Institutes, Technology Alliances, and Personnel Exchange and Liaison programs. Examples are a CRDA for solar-powered rocket engines, the Integrated High-Payoff Rocket Propulsion Technology Program alliance, the Space Technology Alliance, the Space Technology Institute with U.S. academic institutions that have strong space programs, and representatives or on-site engineers at NASA, the NRO, and Princeton University.

These programs are in addition to the myriad of Memoranda of Agreement, Understanding, or Cooperation, symposia/consortia, advisory review panels and steering committee memberships, and regular technology exchange meetings in which AFRL participates, such as the Carbon-Carbon Space

Radiator Partnership, or the National Space and Missile Materials Symposium, the Joint Army, Navy, NASA, Air Force Steering Committee, and industry independent R&D reviews. Some of the AFRL activities include international as well as domestic organizations, such as international forums or formal Data Exchange Agreements with other countries.

The AFRL leverages other Government agency (Ballistic Missile Defense Organization and DARPA) funds by serving as the agent for contracts and grants awarded.

The Air Force Office of Scientific Research (AFOSR) also works cooperatively with the Army, the Navy, and the National Science Foundation in basic research areas. AFOSR has established Partnerships for Research Excellence and Transition in selected research areas that involve consortia of universities and industry in an attempt to bring a fundamental idea to rapid transition into a useful product within about 5 years.

The Warfighter I program is a model for Air Force–industry partnership. The Air Force will fund 25 percent of the development of a Hyperspectral Imagery (HSI) sensor, and Orbital Sciences Corporation (OSC) will fund 75 percent. The sensor will be built commercially and flown on a commercial OrbView satellite operated by OSC. The Air Force will receive near–real time tactical target detection and geolocation, allowing it to evaluate and validate HSI technologies and their military utility in space. In return, OSC will be licensed to sell HSI data commercially. The agreements are being finalized.

5.4 Space Application Trades

Figure J-7 outlines where these findings can be brought to bear on the acquisition process. Any partnering with industry must occur early in the development process to ensure that incremental military requirements can be incorporated into commercial systems. The later in the development process Air Force needs are interjected, the less the system can be influenced, but products, services, and commodities can still be purchased, subject to market factors.

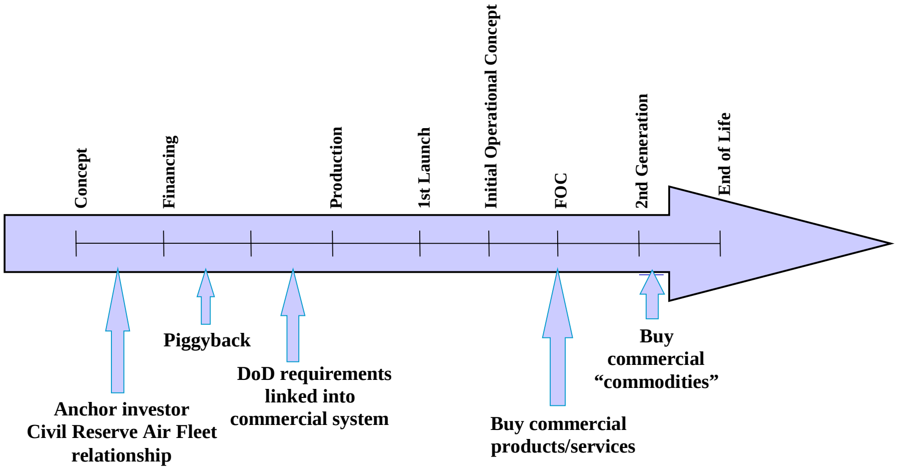

Figure J-7. *Space Application Trades*[4]

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[4] Doug Holker, "Commercial Architecture Study," Aerospace Corporation Paper, 13 May 1998.

6.0 Acquisition Recommendations

A number of recommendations follow from the findings above.

6.1 Marketplace Office

Establish an office within SAF/AQ[5] (or Deputy Under Secretary of Defense/AR) charged with maintaining a database of commercial capabilities currently available and expected to be available in the near term.

- Charter this office to host periodic two-way industry forums to communicate the developing needs of the military and solicit potential commercial solutions. Members of industry would be presented with planning concepts describing future Air Force needs and long-range plans. Industry would also provide input on existing and planned commercial capabilities, as well as comments on possible needed modifications to adapt commercial solutions to the military problems.
- This office should have, as a major responsibility, establishment of informal interchanges with industry to develop and maintain a complete database of militarily useful commercial capabilities (SAF/AQX[6]).
- Charge AF/XO[7] to continually update this database with developing military needs to ensure that Air Force planners have access to the most current commercial availability and that developers have access to evolving needs.
- Finally this office should establish an informal, informational website, styled after the GSA website, designed specifically for Air Force applications. This site would give any office contemplating acquisition of supplies or services a single place to see what is currently or soon to be available in areas such as communications, remote sensing, or other commercial satellite-based products. The website would contain such things as names, capabilities, prices, and points of contact for available services in much the same way that one should be able to determine Federal Express rates or long-distance telephone rates. It should be emphasized that the primary characteristic of this site is to aid planning flexibility, not to institutionalize another procurement requirement.

If properly established and operated, this office and its website would provide a forum for government to publicize requirements and planning options and for industry to comment on requirements and to make commercial capabilities known (OPR: AF/AQ[8], AF/XP[9], and AF/XO).

6.2 Commercial Default

Make commercially produced items the “default” for acquiring capability. Require justification for acquiring other than commercially available services or commodities.

Institutionalize, within DoD or the Air Force, the stipulation that a justification be required, analogous to a sole-source justification, to buy other than commercially available hardware, software, or services.

Where commercial items are defined and available with little or no development required, obtain sufficient proposals or offers and then contract using Firm Fixed Price (FFP) instruments. This contract

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[5] Assistant Secretary of the Air Force, Acquisition.

[6] Assistant Secretary of the Air Force, Acquisition, Management Policy and Program Integration.

[7] Air Force Office of Air and Space Operations.

[8] Air Force Office of Acquisition.

[9] Air Force Office of Plans and Programs.

method establishes a fixed liability for the Government and has the added benefit of discouraging government-directed contract changes. This approach leads to a focus on requirements definition and best price for the Government based on competitive offers, as opposed to the current government emphasis on requirements development and “cost” as a basis for buying.

To enter into an FFP contract, the Government must define the specification for the product or service so that the risk is manageable. This necessitates significant up-front planning, communication, and competence on the part of government and industry procurement personnel. Cost and schedule overruns can still occur if requirements are allowed to “creep.” However, competent management of an FFP contract will increase the probability that costs will be stable, that products will be mature and less likely to change, that schedules are likely to be kept, and that risks are likely to be low.

Where there is a well-defined requirement, a competitive procurement, and an FFP contract, contractor profit is determined solely by market conditions—that is, the offeror with the lowest price meeting the government’s specification provides the product or service. Furthermore, since the marketplace has set the price the Government pays, the Government is assured of obtaining “fair value,” and since the government’s liability is fixed, government oversight can be minimized.

The philosophical difference is that the Government will pay a fair price for the product, and government resources need not be expended to ensure that the contractor does not incur excessive costs, since charges in excess of the contract value cannot be passed along to the Government. With FFP, the product or service is known and the risk is manageable, with contractor profit determined by the marketplace. With the marketplace determining the “fair value” price, the number of “overseers” required to ensure that the Government is getting fair value is reduced.

6.3 Commercial Advocate

Establish a Commercial Advocate, analogous to the “Competition” Advocate, to act as a commercial alternative champion and to assure comprehensive study of commercial items that are, can, or will be available prior to initiating the acquisition of new, Air Force–unique, items (OPR: AF/AQ New Office).

- Charge the Advocate with responsibility for assessing possibilities of piggybacking payloads where technically feasible. Piggybacking in this context may mean placing Air Force payloads on commercial satellites or placing commercial payloads on Air Force satellites. The Advocate will continually assess Air Force and industry requirements for payloads of a size and power requirement that might be placed on a host satellite as opposed to requiring the entire capacity of a satellite. The Advocate will be responsible for facilitating the business case analyses to convince government and industry members of the desirability of taking this piggyback approach.

- This office should highlight the “marginal utility and cost” of military-unique procurements versus buying COTS. This assessment should be used to identify (and document) the marginal return of not buying commercial and cost driving “knees in the military requirement” curves. For example, the last 5 percent of a military requirement may not be commercially available, and may end up as 20 percent of the system cost. Is the last 5 percent worth 20 percent of the cost? Is the last 1 percent worth 10 percent of the cost? AF/XO, AF/XP, and SPO assistance in this requirement analysis will ensure operator “buy-in” as these analyses are undertaken.

- Note: We recognize that the Government buys all commercial items. We define buying commercial products as the government purchase of goods and services where it is not the sole buyer in the marketplace, and thus not solely responsible for development costs.

These analyses may indicate that a non-U.S. system (such as a satellite or launch vehicles) or a non-U.S. provider of communications or other services offers the most cost-effective solution. In this case, changes to law or policy may be required to remove restrictions on procurement through those sources.

6.4 Partnering

Continue to seek opportunities where partnering with industry and or with other government agencies is beneficial. The Air Force Research Lab's Science and Technology activities afford such opportunities.

6.5 Contingency Commercial Capabilities

6.5.1 Background

This section describes a concept to obtain launch, communications, and the other services with a commercial acquisition strategy that contains added mandatory wartime provisions that could be used to augment military core resources both in peacetime and wartime. The concept is patterned after the ongoing Civil Reserve Air Fleet (CRAF) methods. The concept here is temporarily entitled Civil Reserve Space Fleet (CRSF). The CRSF would be a regulatory program based on the Defense Production Act of 1950, Executive Order 12656, and Executive Order 12472 (dated 3 April 1984 and entitled "Assignment of National Security and Emergency Preparedness Telecommunications Functions"). CRSF would utilize space lift or commercial satellite and ground support resources of U.S. carriers to support DoD requirements in a national security contingency. The key rationale for CRSF is in DoD RDT&E (non-recurring) budget savings by avoiding the cost of developing and acquiring systems that are expected to be developed and produced on the commercial market.

The definition of specific contracting methods to obtain services from commercial sources that can be called upon in wartime must be carefully thought out in further study with full participation of potential participants. Furthermore, processes put in place for their use must take into account the dynamics of the marketplace. As discussed in Section 5.0, several viable commercial acquisition approaches can potentially cover many DoD system and service needs; however, priority mandatory mobilization of additional wartime systems and service needs is the issue in this section. The Defense Information Services Agency is the key agency to continue working this issue.

The CRSF would be composed of U.S.-registered space lift (launch) vehicles and/or satellites owned or controlled by U.S. carriers specifically allocated (by Federal Space Agency registration number) for this purpose by the DoT. CRSF vehicles and satellite equipment are those allocated vehicles and space-operated equipment (such as transponders) that a carrier has contractually committed to DoD under stated CRSF conditions. This contractual commitment of the launch vehicles and/or satellite equipment includes the supporting resources required to provide the contract space lift or communication services.[10] The DoC and, for foreign launch sites and other foreign interests, the State Department, will have a role.

6.5.2 Lessons Learned From the Civil Reserve Air Fleet

Desert Storm involved the first formal activation of the CRAF. Prior to that, since its inception, the CRAF carriers had voluntarily participated in regular and routine operations, under contract to the Government, to provide airlift support services to augment the government–owned airlift fleet. However, the magnitude of CRAF operations (large but never more than 40 percent of a carrier's fleet), and timing (in conjunction with the high-volume Christmas holiday season) led to the realization that the CRAF can be activated and that market share can be lost as a result. Many carriers dropped out of CRAF in 1993

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[10] Refer to: (1) Memorandum of Understanding between Secretary of Defense and Secretary of Transportation on CRAF, January 1988, (2) AMC Reg. 55-8, (3) Public Law 85-804 and Executive Order 10789 as amended.

and 1994. On the other hand, there were several non-CRAF participants who came forward to offer equivalent services. The net result was the need to create a variety of flexible incentives to entice the carriers back to CRAF. For example, teaming arrangements among the carriers were allowed and encouraged, but managed by them, to pool their capabilities and to share in Mobilization Value points. One weakness in CRAF is that it gives priority to member carriers in a quid-pro-quo arrangement even if their services may be less than could be obtained on the spot market. Another consideration is that since 1992, airline nationalism has been breaking down and more state-owned airlines have been privatized. (Similar trends are apparent in the satellite and telecom sectors.) Another key lesson learned in the CRAF Desert Storm activation process was that the peacetime business base has to be sufficiently large and robust to justify to each carrier the business case argument that includes the potential reality of CRAF activation. Thus a primary consideration for procuring agency services solicitations is to ensure an adequate, but not dominant, share of business for all CRSF participants. The procuring agency must be fully capable of supporting the necessary market analyses within the acquisition system.

6.6 Develop Innovative Rapid Acquisition Process

Several recent process improvement initiatives, such as the Air Force “Battlelab” process and the Army “Warfighting Rapid Acquisition Program,” have demonstrated or will soon demonstrate the potential to accelerate the fielding of advanced systems and technologies. We recommend initiation of a streamlined process that runs parallel to the entire planning and acquisition process and thus is comprehensive in addressing operational requirements with rapid development of system concepts, technology demonstrations, prototypes, and preproduction planning and approval. For purposes of this report, we will call this process the Rapid Acquisition (RAC) process.

This process would integrate, with as much concurrency and risk as can be managed, all acquisition phases leading up to Milestone IV (production) in order to drastically reduce time to market for selected requirements and/or concepts. The new process would link the appropriate space-related Battlelabs, (such as Space, Information, and UAV) to the formal acquisition process so that successes are achieved quickly and quickly transitioned from experimentation to enhanced warfighting capability. RAC would be managed by a new Air Force office designed to integrate, improve, and control selected efforts of all organizations supporting acquisition. When RAC is in place, the Space Command Commander nominates candidates for RAC based on urgency of need and potential for demonstrating compelling success. Approved candidates are ranked by priority and planned for funding from ATD to advanced concept technology demonstration (ACTD) to operational prototype, and, in selected cases, for pre-EMD or EMD work. (Note: It is the approval and funding for operational prototypes and significant pre-EMD effort that is not in place now. Furthermore, the RAC process would integrate and link ATDs and ACTDs more tightly and ensure a focus on future warfighter capability.)

Risk of failure would be accepted and managed, such that a program could be stopped as quickly as it can be started. Perhaps 50 percent probability of success (for example, 50 percent of all programs started result in a transition to production and operations) would be targeted as a goal indicating the initial risk level for these programs. That goal is compatible with the desire to achieve significant improvements in cycle time, performance, and cost impact and to achieve the desired large output per unit time per dollar. Programs would be tracked and the failure rate would become a key metric to differentiate RAC programs from others with lower cost, schedule, and performance risk.

Cycle time for military products is important even in peacetime due to the rapid pace of change in many technology areas. Often we field systems with costly imminent or existing parts obsolescence and/or severe technology obsolescence. The Air Force objective in setting up details of the RAC process should be to develop a process at least as good as best commercial practices in bringing complex systems into Air Force user hands.

6.7 Air Force Planning Process Outyear Realism

In addition to the normal Air Force planning process, we recommend that a presentation be developed for the Chief of Staff to show what happens to the Future Years Defense Program/POM if the outyears are not optimistically increased as currently planned. This could be presented to the Chief biannually, but must be done to return realism to the outyear planning and to force periodic review of the impact of lessened budgets rather than simply adjusting each year's budget to bow-wave the impact of not getting the "planned" increase while planning for it, unrealistically, in the outyears.

6.8 Revolutionary Approach to Requirements

One strategy we did not discuss in this report is to define our operational needs at a high enough level to ensure we don't overly constrain industry in its response. The Air Force believes its lightning bolts are pushing toward that today. In fact, they could go further. For example, when we decide we want to buy a replacement for our moving-target indication capability, we begin the debate by trying to decide whether it should be space based or airborne. Why not begin by defining the requirement in terms of the products or service needed and let respondents to the RFP determine whether it will be space based, airborne, or a mix? Simplistic in its concept, this thought has numerous structural difficulties: Which command finalizes the requirement, puts money in its budget, and defends the program over its other core needs? Which Air Force Materiel Command product center buys it—the space, airborne, or other center of excellence? Which staffs within the Air Force, Defense, Office of Management and Budget, and Congress do we have to convince of the goodness of the program? What color funding do we appropriate for the effort?

These are all good questions and are clearly outside the scope of this Summer Study. However, the Air Force would be well served to find answers. Today, the questions may be academic. As time goes on, space technology will continue to evolve, spurred on by the ever growing commercial space sector. It will become more and more difficult for the Air Force to continue to define its needs in terms of hardware. Without an infrastructure that can keep up with this external evolution, the Air Force may one day find itself having to abruptly change its ways. Long-range planners should take this on now, while it can be done in an orderly fashion.

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Annex 1 to Appendix J

Tecolote Cost-Estimating Support

1.0 Introduction

Tecolote Research, Inc. (TRI), provided cost-estimating and analysis support to the 1998 Air Force Scientific Advisory Board (SAB) Summer Study, under subcontract to Nichols Research. The study, initially entitled “Going to Space,” was to examine whether it was more cost-effective to move certain missions from ground systems and airbreathing platforms to satellites. The effort for this study was organized around seven panels, one being the Cost-Estimating and Acquisition Strategy Panel (referred to hereafter as “the Cost Panel”), led by Mr. Tom McMahan of Modern Technology Solutions, Inc. This annex to Appendix J summarizes the activities performed by TRI in support of this panel.

This Annex is organized into five main sections, including this introduction. The second section of this Annex discusses the background for this work in the context of the SAB study in general. Section 3.0 describes a major task and deliverable—develop a top-level satellite constellation cost-estimating model that requires only a minimal description of the system being estimated. Section 4.0 describes the other major task—an accounting of the budget reductions and increases due to proposed reduced and discontinued activities, streamlining, and new program costs. This task was accomplished with a series of Excel worksheets showing changes from the 14 January 1998 President’s Budget (PB) and flat projections of this budget to 2020 in real terms. Because this was the first SAB Summer Study with a panel dedicated to cost estimating, lessons learned are provided in Section 5.0 to enhance future efforts.

There are five additional appendices to this Annex. The first is a list of acronyms and abbreviations. Appendix B through Appendix E are not included in this document but can be obtained from the SAB office. Appendix B is a briefing about the Generic Satellite Constellation Cost Model. Appendix C is the Generic Satellite Constellation Cost Model in Microsoft Excel 97 format, with the space-based radar (SBR) parameter inputs and costs. In order to modify and run this model, the associated Automated Cost Estimator Integrated Tool (ACEIT) session (Appendix D), using version 3.1a or later, must be installed and linked to Appendix C. Last, Appendix E is a Microsoft Excel 97 workbook that was used to calculate the budget analysis described in Section 5. ***Caution: Appendices C and E of this report contain sensitive but unclassified data that should not be released without the express permission of the SAB.*** Requests should be directed to Mr. McMahan. Because of the size of Appendices C, D, and E, they were originally delivered to Nichols Research and Modern Technology Solutions, Inc. on a zip disk.

2.0 Background

Cost estimates have become important planning tools in long-range planning studies. The SAB was tasked to make specific and feasible recommendations that would improve the effectiveness of the Air Force in real terms within constant or declining budgets. The Cost Panel was required to estimate the additional cost of potential new programs, as well as the savings achieved by eliminating, reducing, or streamlining existing activities and missions, out to fiscal year 2020 (FY 20). Furthermore, the panel was to recommend and review acquisition strategies that would reduce the cost of future capabilities. The purpose of TRI's support to the SAB study was to provide the cost-estimating and budget analysis to allow assessment of various proposed recommendations.

The Cost Panel developed a plan for the structure of the cost-estimating approach in March 1998, and it was briefed to the other panels' chairs by Mr. McMahan in March and April 1998. At the time this approach was developed (March to May 1998), the panel expected that the other panels would bring in a number of new space system concepts in each of seven "architectures" and that these architectures would be aggregated into a system of systems. The Cost Panel would then evaluate the architectures for their relative cost-effectiveness, affordability, and risk. Due to the organization of the study, there were no systems estimated prior to the Summer Study meeting itself, which took place from 15 to 26 June 1998 in Irvine, California. A cost input form was created and sent to the other panels to solicit their concepts to be estimated. Although the Cost Panel encouraged the other panels to run through at least a trial exercise, the panel ultimately resorted to creating a notional satellite constellation (a constellation of SBRs) to exercise our own process. As it turned out, only four new systems were brought to the Cost Panel for estimating at the Summer Study.

This paragraph briefly describes the trial case developed by the Cost Panel to exercise our process. After it was decided that the Cost Panel would need to create its own trial case (from late April 1998 until after a panel chair meeting in Colorado Springs), a draft description of the system was sent to our panel members by the chairman, with a solicitation for inputs and comments. Providentially, the SBR concept proposed for our trial was very similar to the STARLITE concept managed by the Defense Advanced Research Projects Agency (DARPA). As a result, it was possible to get a much more thorough and thought-through concept description from DARPA (Dr. William Jeffrey, STARLITE program manager). By 18 May 1998, a preliminary draft of a cost estimate of this trial system was briefed to the Cost Panel and subsequently briefed to the panel chairs on 19 May. The core of the structure and methodologies of this estimate remained essentially unchanged through the Summer Study meeting, and the technical parameters were accepted by the Payload Panel as the baseline for the SBR estimate. This estimate is also used to demonstrate the model in Section 4.0 of this Annex.

TRI staff worked part-time on this study until the Summer Study meeting. The majority of effort occurred between April and July 1998, consisting mainly in developing and exercising computer models and spreadsheets, and formatting the output of these tools for presentation. During the Summer Study meeting itself, supported nearly full-time by Mr. Barnum and Mr. Schaefer, the majority of the effort consisted of building the structure for, populating, and then modifying a spreadsheet that contains the 14 January 1998 PB for the Air Force.

3.0 Generic Satellite Cost Model

3.1 Summary

In order to estimate the cost of proposed new systems, TRI developed a summary-level cost-estimating tool for satellite constellations and implemented that methodology in an automated calculation tool. The purpose of this tool is to estimate the cost of a satellite constellation over its life cycle while assisting the user in providing a minimum description of the system. Furthermore, the requirement to project costs in the future as much as 20 years may be beyond the applicability of traditional cost-estimating relationships (CERs) historical data. Satisfying this purpose required the selection of top-level methodologies that are described below. The costs were estimated and accounted for within the framework of a cost breakdown structure (CBS) designed to provide visibility into the major cost drivers but consistent with the summary-level methodologies selected. The various methodologies themselves are described, along with the central issue of applying a cost-discounting factor to account for predicted future cost reductions in space systems. The time phasing of the costs is also described.

Analyses of four separate systems are included in this study. First, as a trial, the methodology was applied to a constellation of SBR satellites with the primary missions of ground moving-target indication (GMTI) and synthetic-aperture radar (SAR) imaging. A life-cycle cost estimate of a program similar to the DARPA-, Air Force-, National Reconnaissance Office (NRO)-sponsored STARLITE (now referred to as "Discoverer II") program was the result of this trial. Second, in order to properly phase and account for the costs from a previous estimate provided for a ground-based laser (GBL) system within the structure of this model, the necessary assumptions were made to re-create this cost estimate with the model's methodology. Third, at a very gross level, the cost of a notional space plane referred to in the study as an aerospace operations vehicle (AOV) was estimated. Fourth, we discuss the cost implications of replacing conventional space point-to-point radio frequency (RF) communications on satellites with a distributed laser communication network although we do not estimate it as a system.

In the hope that it might be useful to future studies of this type, we describe the Microsoft Excel workbook and ACEIT session used to implement our methodology. Briefly, we diagram the structure of this tool, which involves capturing and preprocessing inputs in Excel and passing these to cost-estimating equations implemented in ACEIT. Finally, the estimated costs are returned to Excel for formatting and presentation. The refinement of this tool is beyond the scope of the available resources for the SAB Summer Study task, and we describe some of the limitations and our plans to resolve these.

3.2 Methodology Requirements

The cost-estimating requirements of the SAB Summer Study were unusual in that the technical and programmatic nature of the systems to be estimated were not available prior to the development of the estimating methodology. The potential need to estimate a large variety of future systems in a short period of time with limited resources required that top-level, relatively low-fidelity methods be used. As in all system analysis, there is a tradeoff between field of view and resolution, generality versus fidelity. In the context of high-level future planning, we erred on the side of field of view and generality. One reason this was necessary is that the technical and programmatic details of the concepts brought to the study were summary at best. Most important, the decision makers supported by the study were looking for first-order effects that they could control with decisions best made from their management positions—decisions generally not illuminated by high-fidelity cost modeling. In order to enforce some consistency and discipline across the estimates, we decided to develop a generally useful top-level cost model for satellite constellations, rather than estimate systems on an ad hoc basis as we became aware of them.

There was also a requirement that the model be user friendly. In order to accomplish this, we developed a (mostly) menu-driven Microsoft Excel front end to an ACEIT session, which is described in detail in Section 3.3. Our hope was that other panels, especially the Payloads Panel, could conduct internal trades with this model to explore the trade space prior to submitting concepts to the Cost Panel.

3.3 Discounting of Satellite Cost

There was a consensus on the Cost Panel that the cost of space systems is declining and that CERs based upon historical space systems cost will overestimate the cost of future programs. There are several sound arguments for this position but little supporting data. The first of these arguments is that the commercial space business is rapidly expanding, bringing with this expansion the deflationary pressures of competition and a large base over which to amortize fixed costs. Second, the space industry is maturing. What was once a laboratory-type effort requiring the skills of a few highly educated specialists has become increasingly industrialized, allowing for mass production (as in the case of Iridium). Third, technological advances have increased the availability and reduced the price of the components once unique to specific satellites. In some cases, such as gallium arsenide monolithic microwave integrated circuits, these components have become common in consumer electronics (cellular phones, for example). This increased availability means that many satellite components, and even satellite buses themselves, can be purchased "off the shelf" rather than suffering the cost and delay of development. Last, acquisition reforms should allow the Air Force to leverage these cost savings in procuring militarily useful capability, either through buying commercial services or military-specific satellites.

The Cost Panel needed to be able to model the consensus cost decrease. It seems implausible to us that this trend could continue indefinitely or that it could apply universally to all space systems. However, it does seem likely, for the reasons listed in the previous paragraph, that costs are declining, and it is convenient to model these reductions as a percentage reduction per year in real terms. It became a question of what the percentage reduction per year is and how to apply it.

The only way to correctly demonstrate and quantify these reductions is by collecting data. There was no time to undertake such an effort on this task, and our experience has been that commercial vendors are reluctant to provide such cost data to the Government for proprietary and competitive reasons. In the meantime, the expert judgment of Mr. Barnum was applied with the following logic: We determined the average cost per pound of various general types of satellite hardware. We did the same for ground and space software on a cost–per–source line of code (SLOC) basis. This number for spacecraft buses and communications equipment was derived from the "Unmanned Spacecraft Cost Model," Seventh Edition (USCM7). The time center of this data is about 1992, and reductions were calculated from this date. We then took these cost factors and looked at the effect of various percentage cost reductions over time. We considered the cost reductions in light of the progress to date on lowering satellite costs.

The most aggressive cost-reduction factor we could justify to ourselves was 6 percent. We believe this factor can be applied only to classes of hardware experiencing the most commercialization—communications payloads and spacecraft buses. We believe this factor also may apply to software—given the proliferation of modern software development practices and tools. However, for hardware with little or no commercial interest, it is hard to see how any of the factors leading to cost reduction apply other than to piece parts that are common to commercial satellites. Therefore, for missile warning satellites, little if any reduction would be seen in cost. Table A-1 lists the cost reduction factors in the model, calculated from 1992 to the first year of production, when nearly all the major decisions that could reduce costs would have been made.

Table A-1. *Annual Percent Reduction of Payload Cost From 1992*

Mission Types	*Reduction per Year*
Communications	6%
Navigation	2%
Weather	2%
SAR Imaging	3%
Electro-Optical Imaging	4%
Missile Warning	1%

An important weakness of this model is that it assumes that the year of technology for weight estimates that feed it is 1992. However, there is legitimate expectation that ever more capability can be achieved from every pound of spacecraft. If weight estimates are not properly calibrated, the model will predict poorly and unevenly, and will most likely underestimate future costs leading to weight estimates calibrated below 1992 technology. The only way to avoid this problem is to develop and enforce a standard set of design rules for estimating weight that would be used across systems estimated with this model. However, the same can be said about the application of any weight-based CERs to future system costs, and it must always be a matter for review and intense scrutiny to prevent CERs from being misapplied because of overly optimistic technical inputs.

3.4 Cost Breakdown Structure

Part of the acquisition reform regulations promulgated in the early 1990s mandated the adoption of a standard CBS. Specifically, DoD 5000.4 mandates the use of a MIL-STD-881 CBS for satellite systems. Because the estimates generated for the SAB will not be subject to formal review or approval, it was not necessary to follow this standard to the letter. However, the MIL-STD-881 CBS was used as a starting point. Because of the summary nature of the technical information that we believed would be available on the systems to be estimated, this CBS was trimmed down to 35 estimated items. Of these items, several are estimated with the same methodology and differ only in the acquisition phase in which the costs occur. Table A-2 provides a list of the CBS items. Note that indented items sum to the previous level of indention above. The following series of paragraphs will discuss each of the estimated CBS items. We will not describe the levels of summation above these other than to say that the highest levels are by program acquisition phase—pre–engineering and manufacturing development (pre-EMD), EMD, production, and operations and support (O&S)—and that the costs for these generally occur in that order over time.

3.5 Pre-EMD

Pre-EMD includes all costs that occur prior to EMD, including science and technology directly supporting the program, concept definition studies, and demonstration and validation programs. For now, this item is estimated as a passthrough. In other words, the model does not estimate this, but rather requires the user to take an educated guess. In the case of the SBR system, the pre-EMD costs were a given. DARPA, the NRO, and the Air Force each have committed $200 million to this program for a total of $600 million (one must assume that this is in then-year dollars). It is likely that whatever pre-EMD program evolves, it will be scoped to fit within this budget. This can be considered a large amount of money for a satellite pre-EMD program, but it is appropriate considering the size and complexity of a STARLITE-like program.

Table A-2. *Generic Spacecraft Cost Model Cost Breakdown Structure*

Space System
Pre-EMD Phase
EMD Phase
Prime Mission Equipment
Launch Vehicle Subsystem
Launch Vehicle
Launch Integration
Space Vehicle Subsystem
Space Vehicle Prime Mission Equipment (PME)
Space Vehicle Integration, Assemble, and Test (IA&T)
Space Vehicle Software (Development Only)
Payload
Communications & Digital Electronic
Spacecraft Bus
Shroud (Payload Fairing) & Adapter
Space Vehicle Program Level
Aerospace Ground Equipment
Ground Subsystem
Ground System Integration
Ground System Software
Ground Systems Mission Equipment
Ground Systems Operations Equipment
System Engineering Program Management
Development Fee
Other Government Costs (System Program Office [SPO] Only)
Continuing Development
Production Phase
Prime Mission Equipment
Launch Vehicle Subsystem
Launch Vehicle
Launch Integration
Space Vehicle Subsystem
Space Vehicle PME
Space Vehicle IA&T
Payload
Communications & Digital Electronic
Spacecraft Bus
Shroud (Payload Fairing)
Space Vehicle Program Level
Ground User Equipment
Production Fee
Other Government Costs (SPO Only)

Table A-2. *Generic Spacecraft Cost Model Cost Breakdown Structure (continued)*

Operations & Support Phase
Personnel
Mission Personnel
Operations Personnel
Equipment Maintenance
Mission Equipment Maintenance
Operations Equipment Maintenance
Other Government Costs (SPO Only)

3.6 EMD Launch Vehicle

If the development program will include a launch, the cost of the launch vehicle is collected under the EMD Launch Vehicle CBS element. The following methodology description also applies to the production launch vehicle. Table A-3 was taken from the model itself. It shows the launch vehicle name, the nominal launch costs, and an approximate launch weight into an 800 kilometer, 60°-inclination orbit. Also listed is a rough estimate of the maximum number of launches per quarter that could be reasonably scheduled by a program. The intent was to integrate this model with the National Launch Mission Model so as to appropriately constrain the rate at which a group of systems could be deployed from a launch scheduling perspective. Regrettably, the National Launch Mission Model data came too late to accomplish this, and the peak period of deployment for the two launch-intensive systems modeled (SBR and GBL) did not overlap so as to require this feature. For these two systems, the assumed launch vehicle was an “Evolved Expendable Launch Vehicle [EELV] Light.” The cost of this vehicle and the other EELVs came from the EELV Program Element Monitor (PEM) and was described as a goal based on current Delta, Atlas, and Titan launch costs and the stated EELV program goal of a 25 to 50 percent reduction from current costs.

Table A-3. *Launch Vehicle Choice Table (With Maximum Quarterly Launch Quantity)*

Launch Vehicle	***Nominal Lift (kg)***	***FY 95 $M***	***Max Launches Quantity***
EELV Light	5,442	50,000	1
EELV Medium	8,639	60,000	1.5
EELV Heavy	21,633	130,000	1
EELV Med T2 2013	8,639	50,000	1.5
EELV Heavy T2 2013	21,633	60,000	1
EELV Ultra-Heavy 201	54,422	310,000	1
Pegasus	454	14,000	12
Taurus	1,406	25,000	6
ICBM	1,859	7,000	24
Titan II	2,494	32,000	1.5
Delta II	5,088	59,000	3
Atlas II	6,576	85,000	3
Atlas II AS	8,639	120,000	3
Titan IV/Centaur	18,141	430,000	1.5
Titan IV NUS	21,633	340,000	1.5
STS Shuttle	24,399	450,000	1
Ultra-Heavy	54,422	590,000	1

3.7 EMD Launch Integration

EMD Launch integration includes the cost of preparing and integrating the satellite to the launch vehicle. A Space and Missile Systems Center (SMC) Launch Vehicle Cost Model CER was used to estimate the costs of this element. However, further investigation of this CER is necessary since it may be that this CER should not be used for a prototype integration. If so, a more appropriate CER will be used in future versions of this model.

3.8 EMD Space Vehicle Integration, Assembly, and Test

The EMD Space Vehicle Integration, Assembly, and Test (IA&T) captures the effort to assemble and test the completed satellite. Component and subsystem CERs have their (IA&T) costs embedded in them. This CER is from USCM7 and is described as follows in the ACEIT documentation:

- **DEVELOPMENT CER.** Space vehicle IA&T (nonrecurring)
- **DESCRIPTION.** This USCM7 CER estimates the space vehicle IA&T cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of Spacecraft nonrecurring (including communications) costs.

  This CER estimates nonrecurring costs associated with the effort and activity of designing, developing, manufacturing, and testing of a space vehicle qualification model. For systems that use a protoflight concept, nonrecurring costs include only the portion of the protoflight costs that can be identified as nonrecurring. The cost of acquiring program-specific support equipment, such as mechanical and electrical aerospace ground equipment (AGE), is also considered nonrecurring.

- **SOURCE DATA.** Military, National Aeronautics and Space Administration (NASA), and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using Office of the Secretary of Defense (OSD) published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 16 data points: Atmospheric Explorer (AE), Combined Radiation Exposure Satellite System, Defense Meteorological Support Program (DMSP)-5D1, Defense Satellite Communications System (DSCS) 1&2, Fleet Communications Satellite Program (FLTSAT) 1-5, Global Positioning System (GPS) 1-8, Intelsat IV, MARISAT, NATO3, OSO I, P72-2, P78-1, S3, SMS 1-3, TACSAT, and Telemetry and Data Relay Satellite System (TDRSS).

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.

- **USES.** This CER estimates space vehicle IA&T cost. Although not a satellite subsystem, IA&T contributes to the total cost of a space vehicle. For a component-level estimating model, such as USCM7, there are two distinct groupings of IA&T. The first grouping, subsystem IA&T, addresses the cost of integrating and assembling individual components into a subsystem. In USCM7, subsystem IA&T costs are embedded in the subsystem- and component-level CER values. The second grouping, space vehicle IA&T (estimated by this CER), addresses the cost of integrating and assembling all space vehicle subsystems into an operable space vehicle. These costs are carried under a separate CER in USCM7. Both groupings of IA&T include the cost for all testing effort required to develop the system and accomplish planned test objectives, including the collection of test data. In addition to costs for the space vehicle IA&T discussed above, space vehicle–level costs that cannot be related to any specific space vehicle subsystem are included in the unmanned spacecraft cost model (USCM) definition of space vehicle IA&T costs, which cover IA&T of the space vehicle and payload into a space vehicle. They do not include IA&T of the space vehicle to the launch vehicle.

- **COMMENTS.** Typically, integration and assembly account for 51 percent of the total IA&T while system testing accounts for 49 percent.

- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, average schedule, and average engineering changes. Exercise caution when estimating outside the range of the data.

- **CER**

  IA&T = 850.764 + 0.159 * SCNR, where:
  IA&T = Total nonrecurring space vehicle IA&T cost in thousands of FY 92 dollars, excluding fee
  SCNR = Spacecraft nonrecurring (including communications) cost in thousands of FY 92 dollars, excluding fee

- **DATA RANGE**

	SCNR
Minimum	2,324,000
Maximum	340,094,000
Sample standard deviation	90,778,000

- **STATISTICS**

  Pearson correlation squared = .89
  Multiplicative error = 46%
  Degrees of freedom (SSE) = 14
  Average bias = 0%

3.9 EMD Space Vehicle Software

EMD Space Vehicle Software cost is estimated using a discounted cost per SLOC of $600 (FY 92). The cost reduction due to technology discounting was 6 percent each year since 1992, as described in Section 3.3—Discounting of Satellite Cost. A labor rate of $150,000 per year yields about 20 lines of tested and delivered SLOC per programmer-month in 1992. This number reflects the limited memory of flight hardware, requiring tighter code (although this constraint has eased greatly in recent years) and extensive testing due to the greater difficulty of repairs and greater consequences of failure of flight software.

3.10 EMD Payload

The EMD payload includes the development cost of the satellite mission equipment (for example, instruments, sensors, and associated electronics and mechanisms). It can be the single largest development cost. If there is a prototype, it is included in this cost. In order to minimize the complexity of the model, we adopted a Development to Theoretical First-Unit Production Cost (T1) ratio methodology. The value of this ratio depends on the design legacy from previous hardware. If the payload hardware is a straightforward modification or adaptation of existing designs and hardware, this ratio is one-to-one, and the costs represent the T1 cost of the prototype. If the payload hardware is an off-the-shelf or nondevelopmental item (NDI), the model estimates the EMD payload cost at zero. (Note: Even for an NDI payload, it seems that some test costs would be required to ensure that it will work properly with the new bus.) For medium-legacy hardware the ratio is two-and-a-half to one, and for low legacy the ratio is four to one. It seems unlikely that there would not be a prototype in these cases, but one T1 (the cost of the prototype hardware) is subtracted from both of these ratios if there is not. This T1 ratio methodology is similar to the methodology used by commercial black box cost-estimating models (such as SEER-H of Galorath and Price-H of General Electric). Both these commercial tools ask the cost analyst for a large number of inputs to determine these ratios, the most important of which is design legacy. Our summary-level methodology requires the answer to one question: Is the new payload very similar, somewhat similar, or not at all similar to existing payload designs? There may be a number of considerations, but experienced engineers should be able to come to a consensus.

3.11 EMD Communications and Digital Electronics

The EMD communications and digital electronics element includes the cost for the wideband communications (not low-data-rate telemetry, tracking, and command [TT&C] functions) and associated data formatting functions. The interface between the payload and this item should come at the unformatted data stream from the payload. This dollars-per-pound cost factor (1992 dollars) comes from the communications subsystem CER in USCM7. The ACEIT documentation for this CER is as follows:

- **DEVELOPMENT CER.** Communications payload (COMM) subsystem (nonrecurring).

- **DESCRIPTION.** This USCM7 CER estimates the communications subsystem cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of the COMM subsystem weight.

This CER estimates nonrecurring costs associated with the effort and activity of designing, developing, manufacturing, and testing of a space vehicle qualification model. For systems that use a protoflight concept, nonrecurring costs include only a portion of the protoflight costs that can be identified as nonrecurring. The cost of acquiring program-specific support equipment, such as mechanical and electrical AGE is also considered nonrecurring.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on seven data points: DSCS 1&2, FLTSAT 1-5, GPS 1-8, Intelsat IV, MARISAT, NATO3, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.

- **USES.** This CER estimates the communications subsystem cost.

  The communications mission equipment subsystem is found only on satellites with a communications mission. Communications (mission equipment) subsystems perform a transmission repeater and signal conditioning function. Much of the communications subsystem equipment is similar to the TT&C's. Typical equipment includes receiving antennas, receivers, traveling-wave tube amplifiers, transmitters, transmitting antennas (earth coverage, narrow beam, shaped beam), RF switches, switch control units, phased-array controls, signal processors, digital processors, modems, and crypto cards. In addition to costs for the hardware items discussed above, any non-hardware accounts for effort directly associated with the communications subsystem are included.

  When technical definition is available, it is beneficial to break out the communications subsystem into its major components, estimate their cost using dedicated CERs, and aggregate the results to arrive at subsystem cost.

- **COMMENTS.** TACSAT was deleted from the database used to generate this CER because it had no transmitter data.

- **LIMITATIONS.** The minimum probable error (MPE) CERs have "positive" average bias (ranging from a low of 1 percent to a high of 29 percent, with 8 percent typical). This indicates that the MPE CERs tend to overestimate the hypothesized equation. Therefore, the user should be cautious when making an estimate using an MPE CER. Under no circumstances should these MPE CERs be used outside the data range. In addition, since the point estimate generated from MPE CERs represents no readily identifiable property of a distribution, it should not be used in a risk analysis. Finally, do not mix the use of MPE and minimum unbiased probable error (MUPE) USCM7 CERs in the same estimate. MUPE CERs have no positive bias and estimate a rue expected value.

- **CER**

  COMM = 168.575 * COMWT, where:
  COMM = Total nonrecurring communications subsystem cost in thousands of FY 92 dollars, excluding fee
  COMWT = Communications subsystem weight (lbs)

- **DATA RANGE**

	COMWT
Minimum	144.2
Maximum	871.4
Sample standard deviation	275.8

- **STATISTICS**

  Pearson correlation squared = .86
  Multiplicative error = 46%
  Degrees of freedom (SSE) = 6
  Average bias = 18

3.12 EMD Spacecraft Bus

The EMD spacecraft bus item covers the cost of all satellite hardware not covered in the payload of the wideband communications CBS item. It includes electrical power, thermal control, Attitude Determination Control System (ADCS), structures, and TT&C communications. The ACEIT documentation of this CER is as follows:

- **DEVELOPMENT CER.** Spacecraft (nonrecurring).
- **DESCRIPTION.** This USCM7 CER estimates the spacecraft cost in thousands of FY 92 dollars excluding fee. Cost is estimated as a function of spacecraft weight.

  This CER estimates nonrecurring costs associated with the effort and activity of designing, developing, manufacturing and testing of a space vehicle qualification model. For systems that use a protoflight concept, nonrecurring costs include only the portion of the protoflight costs that can be identified as nonrecurring. The cost of acquiring program-specific support equipment, such as mechanical and electrical AGE, is also considered nonrecurring.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 12 data points: AE, DMSP-5D1, DSCS 1&2, FLTSAT 1-5, GPS 1-8, Intelsat IV, MARISAT, NATO3, OSO I, SMS 1-3, TACSAT, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.
- **USES.** This CER estimates spacecraft cost. The spacecraft, often called the bus or platform, consists of structure, ADCS, thermal control, electric power system (EPS), TT&C, and apogee kick motor (AKM) subsystems.
- **COMMENTS.** CRRES was deleted from the database used to generate this CER because the costs did not represent a full design effort.
- **LIMITATIONS.** For satellite test programs (P78-1, P78-2, P72-2, and S3) use an alternate USCM7 equation: Y=10.213 * (spacecraft weight). This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes.

- **CER**

  SC = 39.608 * SCWT, where
  SC = Total nonrecurring spacecraft cost in thousands of FY 92 dollars, excluding fee
  SCWT = spacecraft weight (lbs)

- **DATA RANGE**

	SCWT
Minimum	520.0
Maximum	2543.2
Sample Standard Deviation	538.0

- **STATISTICS**

  Pearson correlation squared = .95
  Multiplicative error = 33%
  Degrees of freedom (SSE) = 11
  Average bias = 0%

3.13 Shroud (Payload Fairing) and Adapter

The shroud and adapter CBS item is the cost of the shroud for the prototype flight, if any. It is assumed that the shroud is an NDI. The following is a description of the CER from USCM7:

- **PRODUCTION CER.** Payload fairing total cost (recurring)
- **DESCRIPTION.** This CER estimates launch vehicle payload fairing recurring total costs in thousands of FY 94 dollars, excluding cost of money and fee. Cost is estimated as a function of payload fairing volume and total production run quantity.

  This CER estimates the lot total cost (LTC) of the recurring hardware for whatever quantity is input into the CER.

- **SOURCE DATA.** Cost and technical data were obtained from the Atlas, Delta, and Titan system program offices, cost performance reports, cost data summary reports, General Dynamics Corporation, and the Aerospace Corporation at Vandenberg AFB.

  This CER is based on the following data points: Atlas IIA 11', Atlas IIA 14', Delta II 10', Titan IV 56', Titan IV 66', Titan IV 76', and Titan IV 86'.

- **REFERENCES.** “Launch Vehicle Cost Model Update,” TRI, CR-0734, 23 August 1995.
- **USES.** This CER was developed for use in estimating recurring total costs for launch vehicle payload fairings. Use this Total Cost CER form versus the T1 or Total Direct Cost forms if you do not have specific overhead and general and administrative rates.

  This equation estimates an LTC for the specified quantity. It is not necessary to make ACE adjust these results for learning-curve effects.

- **LIMITATIONS.** This CER has mediocre fit statistics.

- **CER**

  PLF_RTC = 0.00010 * PLF_VOL^1.1098 * P_QTY^0.9596, where:
  PLF_RTC = Payload fairing recurring total cost in thousands of FY 94 dollars, excluding cost of money and fee, including overhead, and general and administrative rates
  PLF_VOL = Payload fairing volume in cubic inches
  P_QTY = Total production run quantity

- **DATA RANGE**

#OBSV	MIN	MAX
PLF_RTC7	$14,558	$172,040
PLF_VOL7	997,142	27,017,697
P_QTY7	3	20

- **STATISTICS**

Adjusted R-square	63.95%
Standard error (log space)	0.4904
Mean absolute deviation (MAD) of error	25.32%
Coefficient of variation (se/mean)	25.80%
t-Score (PLF_VOL)	3.53
t-Score (P_QTY)	2.71

3.14 EMD Program Level

The EMD program-level element pays for the systems engineering and program management of the space vehicle development effort. It is treated as a cost-on-cost equation with the other space vehicle development costs. The ACEIT documentation for this CER is as follows:

- **DEVELOPMENT CER.** Program level (nonrecurring).

- **DESCRIPTION.** This USCM7 CER estimates the program-level cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of space vehicle total nonrecurring cost.

  This CER estimates nonrecurring costs associated with the effort and activity of designing, developing, manufacturing, and testing of a space vehicle qualification model. For systems that use a protoflight concept, nonrecurring costs include only the portion of the protoflight costs that can be identified as nonrecurring. The cost of acquiring program-specific support equipment, such as mechanical and electrical AGE, is also considered nonrecurring.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 17 data points: AE, CRRES, DMSP-5D1, DSCS 1&2, FLTSAT 1-5, GPS 1-8, Intelsat IV, MARISAT, NATO3, OSO I, P72-2, P78-1, P78-2, S3, SMS 1-3, TACSAT, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.

- **USES.** This CER estimates the program-level cost. The program level includes accounts for program management, reliability, planning, quality assurance, systems analyses, project control, and other costs that cannot be related to any specific area of activity. System test is no longer included in this area, a departure from previous editions of USCM. Program-level activities are grouped into (1) program management, (2) systems engineering, and (3) data.

- **COMMENTS.** Typically, program management accounts for 50 percent; systems engineering, 43 percent; and data, 7 percent of total program-level costs.
- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. Exercise caution when estimating outside of the range of the data.
- **CER**

PL = 1.487 * SVNR^0.841, where:
PL = Total nonrecurring program-level cost in thousands of FY 94 dollars, excluding fee
SVNR = space vehicle (spacecraft + communications + IA&T) total nonrecurring cost in thousands of FY 92 dollars, excluding fee

- **DATA RANGE**

	SVNR
Minimum	3,961.1
Maximum	450,349.7
Sample standard deviation	113,220.3

- **STATISTICS**

Pearson correlation squared = .93
Multiplicative error = 36%
Degrees of freedom (SSE) = 15
Average bias = 0%

3.15 EMD Aerospace Ground Equipment

EMD AGE includes the cost of a qualification model of the space vehicle. The ACEIT documentation for this methodology is as follows:

- **DEVELOPMENT CER.** AGE (nonrecurring).
- **DESCRIPTION.** This USCM7 CER estimates the AGE cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of space vehicle total nonrecurring costs.

  This CER estimates nonrecurring costs associated with the effort and activity of designing, developing, manufacturing, and testing of a space vehicle qualification model. For systems that use a protoflight concept, nonrecurring costs include only the portion of the protoflight costs that can be identified as nonrecurring. The cost of acquiring program-specific support equipment, such as mechanical and electrical AGE, is also considered nonrecurring.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

This CER is based on nine data points: AE, CRRES, DMSP-5D1, GPS 1-8, Intelsat IV, MARISAT, NATO3, SMS 1-3, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.
- **USES.** This CER estimates AGE cost. AGE refers to ground support equipment (electrical and mechanical) required to support the space vehicle during ground test and preparation for flight operations. All AGE costs are categorized as nonrecurring. In addition to costs for plant equipment, special materials handling equipment, tooling, and test equipment, any non-hardware accounts for effort directly associated with AGE are included in the USCM definition of AGE costs.
- **COMMENTS.** FLTSAT 1-5, TACSAT, DSCS 1&2, and OSO I were deleted from the database used to generate this CER because of unexplained low AGE cost relative to total nonrecurring costs. No parametric relationships could be found among space test programs (P78-1, P78-2, P72-2, and S3). The mean cost ($1,067,000) and the standard deviation ($1,007,000) for space test programs are submitted for consideration only.
- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. Exercise caution when estimating outside of the range of the data.
- **CER**

  AGE = 7.228 * SVNR^.642, where
  AGE = Total nonrecurring AGE cost in thousands of FY 92 dollars, excluding fee
  SVNR = Space vehicle (spacecraft + communications + IA&T) total nonrecurring cost in thousands of FY 92 dollars, excluding fee

- **DATA RANGE**

	SVNR
Minimum	21,035.8
Maximum	500,117.7
Sample standard deviation	152,455.8

- **STATISTICS**

  Pearson correlation squared = .84
  Multiplicative error = 34%
  Degrees of freedom (SSE) = 7
  Average bias = 0%

3.16 EMD Ground System Integration

This CBS item is the cost of integrating the ground elements. The methodology comes from the Electronic Systems Division and is a cost-on-cost factor with the other ground system costs. ACEIT contains the following description of this methodology:

- **DEVELOPMENT COST FACTOR.** I&A.
- **DESCRIPTION.** Estimates EMD I&A costs as a percentage of EMD \

- **SOURCE DATA.** An analysis was made of 69 CPRs and C/SSRs stored in ACEIT’s Automated Cost Database. All were from Electronic Systems Center (ESC) EMD contract efforts occurring between 1970 and 1992. The monthly cost data from these reports were normalized to thousands of FY 90 dollars using monthly OSD inflation indices. On average, the 69 EMD efforts were 92.3 percent spent (such as, cumulative ACWP/LRE). You can view this data set in CO$TAT by loading file “ESC_DEV.”

- **REFERENCES.** ESCP 173-2A, “Acquisition Support Cost Factors and Estimating Relationships,” November 1993. Also, see “ESC/FMC Acquisition Support CERs and Factors,” TRI CR-0672, September 1993.

- **USES.** Use this factor as a gross check on your primary estimating methodology. Use it as your primary method only when you have a quick reaction, tradeoff, or planning estimate and no specific method exists (for example, cost/CER/factor from analogous programs).

  You can use CO$TAT to select an analogous cost or create a CER/factor from analogous systems. Try the same form of equation presented here. CO$TAT provides the “ESC_DEV” data set that contains PMP and support costs on 69 EMD contracts.

- **LIMITATIONS.** Generally, factors are not as good as CERs. The data have a wide variation about the mean, that is, COEF VAR = (STD DEV/MEAN) * 100, which makes factors less able to predict costs.

- **STATISTICS (I&A_F)**

MEAN	MEDIAN	STD DEV
COEF VAR	#OBSV	#MISG
LOW	HIGH	MAD%
17.3	9.1	25.7
148.6%	33	36
1.0	144.7	259.0

- **FACTOR**

  I&A_F = (0.173) x (PMP_F - I&A_F), where:
  PMP_F = Prime mission product (EMD), not including I&A
  I&A_F = Integration & assembly (EMD)

- **DATA RANGE (thousands of FY 90 dollars)**

	LOW	HIGH
PMP_F	1,124	1,397,622
I&A_F	53	64,360

3.17 EMD Ground System Software

The ground system software was estimated on a dollars-per-SLOC basis. In this case, we estimated the ground software at $200 per SLOC, in FY 92 dollars. As with the flight software, this cost was discounted for technology improvement effects at 6 percent a year. Generally, the memory and processing power available on the ground are greater than in space. This relaxes the requirement of “tight code” on the developers. Ground software is easier to diagnose, repair, and maintain. Furthermore, the likelihood of severe or unrecoverable effects on the health and status of the satellite is lower; therefore redundancy and testing requirements can be relaxed in comparison to flight software. As a result, ground software is significantly more affordable than flight software (by a factor of 3 in this case). Two hundred dollars per SLOC translates into roughly 60 lines of code per programmer-month (at $150,000 per programmer year in FY 92 dollars).

It should be noted that there are some development projects that claim to be outperforming our prediction of a 6 percent improvement per year. TRW, working on the Ballistic Missile Defense Organization’s System Engineering and Integration project, claims to be producing more than 200 lines of code per programmer-month (1997). On a more cautious note, SLOC is a crude measure of software complexity and difficulty that is dependent on programming language, style, and counting rules. Most likely, TRW’s programmers are using a fourth-generation language. While certainly easier to learn and use than their more cryptic predecessors, these languages tend to require more SLOC to accomplish the same functionality. Therefore, as in the case of the weight estimates, it is important that the SLOC estimates be properly and consistently calibrated in order for this methodology to be applied correctly.

SAB study participants were not prepared to provide sizing estimates of the software requirements for their concepts or programs by any measure, and certainly not by SLOC. It is standard systems engineering practice to conduct a software functional analysis and code sizing by computer software configuration item in the concept definition phase of a program. The fact that no analysis had been conducted for the concepts estimated, including the SBR, suggests that even this crude method of software cost-estimating might be too refined for these advanced concepts.

3.18 EMD Ground Systems Mission Equipment

The EMD ground systems mission equipment item is estimated off-line or with a passthrough. Because of the diversity of the possible missions, it was impossible to envision a general ground system model that could estimate the range of alternatives expected for mission-specific equipment. The usual approach was to get a general description of the ground mission equipment. Using this description, the panel attempted an analogous rough order-of-magnitude estimate to existing systems. In the case of the SBR, a previous rough cost had already been estimated by the STARLITE program office. Seeing nothing wrong with their approach, we adopted their estimate. In the case of the GBL estimate, the task was complicated by the existing total estimate that was provided as a ground rule. Therefore, estimating this and all other GBL costs became more of an exercise in cost allocation than in cost estimation.

This CBS item points to a weakness of the model methodology that is difficult to correct. In an attempt to make the methodology as general as possible and requiring as few inputs as possible, we sacrificed the ability to require specific parameters that would allow the estimating of the broad range of possible systems. Asking for a passthrough estimate, as we have here, ignores the need to estimate multiple ground systems, and hands the program estimate over to the analyst. We recommend that in future uses of this model, ground system CERs appropriate to the majority of space missions be incorporated as an alternative to a passthrough estimate.

3.19 EMD Ground Systems Operations Equipment (Satellite Operations Center)

EMD ground systems operation equipment includes the development cost of the equipment for the TT&C functions normally housed within a Space Operations Center (SOC). Because the complexity of this equipment is linked to the complexity of the mission equipment, it is estimated with the same nonrecurring-to-recurring cost ratio used for the flight hardware as described in Section 3.10 (1 for high-legacy programs, 2.5 for medium, and 4 for low). However, at the SAB meeting, the possibility of segregating mission operations from TT&C operations was seriously considered. If that were indeed pursued, it would be hard to justify a low-design legacy for these functions, reducing the estimate in the low-design legacy cases. If the TT&C functions could be truly isolated and standardized, development costs could eventually be reduced to the T1 cost of the equipment needed for the prototype. In that case this methodology should be revisited and adjusted downward.

3.20 EMD System Engineering Program Management

EMD system engineering program management item covers the cost of the system design engineering and program management in the EMD phase. The activities covered by this item are listed in detail below. It is estimated with a cost-on-cost CER from USCM7 that uses the development cost as its argument, excluding fee but including IA&T. It is important to apply these factors in the correct order. The following is the ACEIT documentation for this CER:

- **DEVELOPMENT CER.** Program level (nonrecurring).
- **DESCRIPTION**. This USCM7 CER estimates the program-level cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of space vehicle total nonrecurring cost.

  This CER estimates nonrecurring costs associated with the effort and activity of designing, developing, manufacturing, and testing of a space vehicle qualification model. For systems that use a protoflight concept, nonrecurring costs include only the portion of the protoflight costs that can be identified as nonrecurring. The cost of acquiring program-specific support equipment, such as mechanical and electrical AGE, is also considered nonrecurring.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 17 data points: AE, CRRES, DMSP-5D1, DSCS 1&2, FLTSAT 1-5, GPS 1-8, Intelsat IV, MARISAT, NATO3, OSO I, P72-2, P78-1, P78-2, S3, SMS 1-3, TACSAT, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.
- **USES.** This CER estimates program-level cost. The program level includes accounts for program management, reliability, planning, quality assurance, systems analyses, project control, and other costs that cannot be related to any specific area of activity. System testing is no longer included in this area, a departure from previous editions of USCM. The program-level activities are grouped into (1) program management, (2) systems engineering, and (3) data.
- **COMMENTS.** Typically, program management accounts for 50 percent; systems engineering, 43 percent; and data, 7 percent of total program-level costs.
- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. Exercise caution when estimating outside the range of the data.
- **CER**

  PL = 1.487 * SVNR^0.841, where
  PL = Total nonrecurring program-level cost in thousands of FY 92 dollars, excluding fee
  SVNR = Space vehicle (spacecraft + communications + IA&T) total nonrecurring cost in thousands of FY 92 dollars, excluding fee

- **DATA RANGE**

	SVNR
Minimum	3,961.1
Maximum	450,349.7
Sample standard deviation	113,220.3

- **STATISTICS**

Pearson correlation squared = .93
Multiplicative error = 36%
Degrees of freedom (SSE) = 15
Average bias = 0%

3.21 Development Fee

The development fee item covers the fee or profit awarded to the contractor and subcontractors responsible for the development effort. The methodology is a cost-on-cost percentage specified by the user, using all development costs except government costs as the base. As a default, the model uses 15 percent of non-government pre-EMD and EMD costs.

There was increased interest in a variety of commercial acquisition approaches that would make the estimating of an explicit fee or profit superfluous, as visibility into the cost makeup of the price offered the Government became more limited. It remains a challenge to develop methodologies that can be applied to various commercial acquisition approaches.

3.22 EMD Other Government Costs (SPO Only)

EMD other government costs (SPO only) includes the burdened cost of Space Program Office (SPO) military, government civilian, specialty engineering and technical assistance (SETA) contractors, and Federally Funded Research and Development Center (FFRDC) personnel. The burdens on military and government civilians include travel, training, retirement pay, and all other burdens found in the Cost and Planning Factors manual (AFI 65-503). SETA and FFRDC personnel costs are fully burdened (general and administrative costs and fee), and as such are not included in the base for fee above. The model estimates the number of SPO personnel based on a rolling time average of the development costs. The premise behind this logic is that, historically and in general, the government engineering and management of a satellite program has been divided into major work packages and support functions. The larger the dollar value, the greater the complexity and the more SPO personnel required. On the support side, the reporting requirements and efforts increase with the size of the program. The rolling time averaging technique used reflects the reality that it is impossible to increase staff and reduce staff in the year that costs are incurred. This window for the rolling average is 5 years, reflecting a 2-year lead and lag in SPO staffing to obtain, obligate, and then manage financial resources in the year the cost is incurred.

This methodology should be considered preliminary. The amount of staff per million dollars varies according to the program phase. Furthermore, the dollars per person depend on the level of acquisition reform. In the pre-EMD and EMD phases, we assume that an SPO staff person would be required for every \$2 million, \$5 million, or \$10 million expended by the program office, depending on the level of acquisition reform—traditional, reformed, or revolutionary. For example, an SPO spending \$100 million per year would require 50, 20, or 10 government people to manage it. These factors clearly overestimate the size of an SPO for large programs and underestimate it for smaller ones. A more accurate form of such an equation is probably A + B * \$^C, where A is some constant effort required no matter how small the program and C is an exponent between 0 and 1 that accounts for the economies of scale of managing large programs. However, determining the constants, coefficients, and exponents would require a data collection and cost analysis beyond the scope of this effort. Streamlining would be facilitated by a reduction in required SPO activities, not just performing the current activities with fewer people. This could ultimately require acquisition policy changes or even congressional action. Nevertheless, the dollars-per-person metric might be useful as a rough gauge of the progress of acquisition reform. Data should be periodically collected and analyzed.

Finally, the burdened rates we used in thousands of 1998 dollars for the military, government civilian, SETA, and FFRDC are 100, 80, 150, and 200 respectively. Of course, there are many factors, such as grade-level mix and SETA/FFRDC selection, that would affect this, but again, this is a top-level model that intentionally does not request the information from the user that could be used to make such distinctions. However, these rates will be made easier to adjust by placing them in the Cost Inputs worksheet of the model. Currently, these rates are accessible in the lower rows of the Cost Details worksheet.

3.23 Continuing Engineering and Manufacturing Development

The continuing EMD CBS item was inserted to reflect our observation that no SPO of has ceased development activity at the conclusion of its EMD program. These ongoing activities normally involve resolving or mitigating engineering difficulties, enhancing mission effectiveness, inserting technology, or addressing user concerns and desires. We have treated this cost as a factor of the prime mission equipment (PME) development cost, both space and ground. There are two portions of this cost: the ongoing development and a periodic prototype flight or experiment. The ongoing development percentage is assessed every year, and the flight percentage—higher amount—is assessed with a period specified by the user. These percentages will vary due to the pressure for upgrades to a system, but our expert opinion suggests that the ongoing development be 10 percent of the PME and that the periodic flight percentage be 50 percent. All three of these parameters are accessible from the management section of the model's Inputs screen.

Some programs, such as GPS, have programmatically experienced this cost as "block upgrades." If this cost modeling were being done at a more detailed level, it would be appropriate to model the effect on the production learning curve of these ongoing developments, and to take design changes into account. However, at the summary level being considered by this model, we feel that a more general recognition and accounting for these costs is appropriate.

3.24 Production Launch Vehicle

The production launch vehicle is the first of the production CBS items. There is no difference between this estimating method and that used in EMD launch vehicle. The details of the logic of how satellites are deployed over time on the launches are discussed in Section 3.35. The cost for a launch is incurred in the year before the launch takes place.

3.25 Production Launch Integration

Production launch integration is the production phase equivalent of the EMD launch integration CBS item described above. There is no difference between the methodologies. Note: Neither the launch vehicle nor the launch integration methodology has learning applied. The individual launch vehicle costs are passthroughs (see Table A-3) from the launch PEM, and it is assumed that the launch costs are determined primarily by other factors; however, one would expect experience to allow improvement of the launch vehicle integration process. To maintain consistency with the June 1998 estimates, we have not modified this model in any way since 17 June 1998, but we recommend that learning be applied to this CBS item in future versions of the model.

Another important factor that is currently not addressed in this model is the complexity of the vehicle stack. The model has been set up explicitly to allow for multiple satellites to be launched on a single launcher. This practice is commonplace today (for example, Iridium); however, it is intuitive that the complexity of launch integration would increase with the number of satellites being launched simultaneously. Data on this effect on launch integration costs have not been collected or analyzed sufficiently to apply a factor.

3.26 Production Space Vehicle IA&T

The production space vehicle IA&T item includes the recurring cost of IA&T of the space vehicle. For this item, we chose to use the "Unmanned Spacecraft Cost Model," Sixth Edition (USCM6) Small Satellite Cost Model rather than USCM7 because USCM7 uses as its argument the payload and communications weight rather than cost. We have attempted to capture the complexity of systems on a cost-per-pound basis. The USCM7 weight-based CER for integration would not distinguish between highly complex payloads and simple payloads and charges 4,000 (1992) dollars per pound across the board. The 5.4 percent of the recurring cost form of this equation is more satisfying if you believe that complex and therefore expensive payloads will cost more to IA&T than simple and relatively inexpensive ones. Furthermore, while the statistical approach used in USCM7 (MUPE) and USCM6 (least square, best fit) are not directly comparable, in this case, the USCM6 statistics are clearly better.

- **PRODUCTION CER.** Space vehicle I&A.
- **DESCRIPTION.** This USCM6 Small Satellite CER estimates the space vehicle I&A cost in thousands of FY 86 dollars, excluding fee. Cost is estimated as a function of space vehicle first-unit cost. This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. This CER estimates recurring costs associated with the effort and activity of fabricating, manufacturing, integrating, assembling, and testing of the space vehicle flight hardware. In addition, all efforts associated with the launch and orbital operations support of a program are considered to be recurring costs. Contractors typically accumulate recurring program costs in total, rather than by specific production units. As a result, historical data had to be adjusted to reflect a theoretical first-unit cost for the purpose of developing the recurring CERs. This adjustment was accomplished by assuming a cumulative average learning curve with a 95 percent slope. Using this assumption and the number of units consecutively produced for each space vehicle program, the set of first-unit costs was obtained for generating the recurring cost for this CER.
- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch). In selecting the subset of the USCM6 database for developing the small satellite CERs, a small satellite was defined not only in terms of size, but in terms of acquisition philosophy (less than $25 million FY 86 for the first-unit production cost and less than 1,400 pounds combined bus and space vehicle weight).

  This CER is based on six data points: AE, IDCSP, MARISAT, NATO3, P78-2, and S3.
- **REFERENCES.** "USCM6 Small Satellite and Revised Small Satellite Excursion," TRI, 21 November 1991.

- **USES.** This CER estimates I&A (space vehicle–level) cost. Although not a satellite subsystem, I&A contributes to the total cost of a space vehicle. For a component-level estimating model, such as USCM6, there are two distinct groupings of I&A. The first grouping, subsystem I&A, addresses the cost of integrating and assembling individual components into a subsystem. In USCM6, subsystem I&A costs are included in the subsystem and component-level CER values. The second grouping, space vehicle I&A (estimated by this CER), addresses the cost of integrating and assembling all space vehicle subsystems into an operable space vehicle. In addition to costs for the space vehicle–level I&A discussed above, space vehicle–level costs that cannot be related to any specific space vehicle subsystem are included in the USCM definition of space vehicle I&A costs. These I&A costs cover I&A of the space vehicle and payload into a space vehicle. They do not include I&A of the space vehicle to the launch vehicle.

- **LIMITATIONS.** Exercise caution when estimating outside the range of the data.

- **CER**

  I&A = .054 * SCFU, where:
  I&A = First-unit cost of I&A in thousands of FY 86 dollars
  SCFU = Space vehicle first-unit cost in thousands of FY 86 dollars

- **DATA RANGE**

	SCFU
Minimum	1610.7K
Maximum	15053.3K

- **STATISTICS**

  R-square = .91
  Adjusted Rs square = .89
  Standard error = 184.22
  F-score = 50.93
  Sig-F = .0008

3.27 Production Payload

Production payload includes the recurring production cost of the mission equipment (for example, instruments, sensors, and associated electronics and mechanisms). It is estimated on a cost-per-pound basis, de-escalated from 1992 to the first year of production. The cost per pound (in thousands of 1992 dollars) and the rate of de-escalation depend on payload type as discussed above. The de-escalation is calculated from 1992 until the first year of production, because at that point the major design decisions and production processes that could affect cost have been made or put in place. This CBS item is one of the largest costs, if not *the* largest cost, in the model. Typically, these costs would be modeled as separately costed payload components. These multiple CERs would be able to differentiate the costs of the payload being estimated from others of its type. Here, for simplicity's sake again, no such differentiation is possible, and we must be content with the hope that the weight provided as an input will be representative of the overall complexity and extent of the effort.

3.28 Production Communications and Digital Electronic

Production communications and digital electronics includes the recurring production cost of the wideband mission data equipment (not TT&C), if any. It is estimated on a cost-per-pound basis, de-escalated from

1992 to the first year of production. The de-escalation is calculated from 1992 until the first year of production, because at that point the major design decisions and production processes that could affect cost have been made or put in place. The cost per pound comes from a USCM7 CER. The ACEIT documentation of this CER is as follows:

- **PRODUCTION CER.** Space vehicle (recurring).

- **DESCRIPTION.** This USCM7 CER estimates the space vehicle cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of spacecraft weight and communications total weight.

  This CER estimates recurring costs associated with the effort and activity of fabricating, manufacturing, integrating, assembling, and testing of the space vehicle flight hardware. In addition, all efforts associated with the launch and orbital operations support of a program are considered to be recurring costs.

  Contractors typically accumulate recurring program costs in total, rather than by specific production units. As a result, historical data had to be adjusted to reflect a theoretical first-unit cost for the purpose of developing the recurring CERs. This adjustment was accomplished by assuming a cumulative average learning curve with a 95 percent slope. Using this assumption and the number of units consecutively produced for each space vehicle program, the set of first-unit costs was obtained for generating the recurring cost for this CER.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 12 data points: DSCS 4-7, DSCS 8-14, FLTSAT 1-5, FLTSAT 6-8, GPS 1-8, GPS 9-11, GPS 13-40, Intelsat IV, MARISAT, NATO3, TACSAT, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.

- **USES.** This CER estimates space vehicle cost. Space vehicle is the sum of IA&T, structure and interstage, ADCS, thermal control, EPS, TT&C, AKM, communications payload, and program-level support.

- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. Exercise caution when estimating outside of the range of the data.

- **CER**

  SC = 38.533 * (SCWT + COMWT), where:
  SC = First-unit cost of space vehicle in thousands of FY 92 dollars, excluding fee
  SCWT = Spacecraft weight (lbs)
  COMWT = Communications total weight (lbs)

- **DATA RANGE**

	SCWT + COMWT
Minimum	664.8
Maximum	3391.1
Sample standard deviation	774.4

- **STATISTICS**

  Pearson correlation squared = .54
  Multiplicative error = 30%
  Degrees of freedom (SSE) = 11
  Average bias = 0%

3.29 Spacecraft Bus

The spacecraft bus CBS item includes the recurring production cost of the satellite bus. It is estimated on a cost-per-pound basis, discounted from 1992 to the first year of production. The technology discounting is calculated from 1992 until the first year of production because at that point the major design decisions and production processes that could affect cost have been made or put in place. The cost per pound comes from a USCM7 CER. The ACEIT documentation of this CER is as follows:

- **PRODUCTION CER.** Spacecraft (recurring).
- **DESCRIPTION.** This USCM7 CER estimates the spacecraft cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of spacecraft weight.

  This CER estimates recurring costs associated with the effort and activity of fabricating, manufacturing, integrating, assembling, and testing of the space vehicle flight hardware. In addition, all efforts associated with the launch and orbital operations support of a program are considered to be recurring costs.

  Contractors typically accumulate recurring program costs in total, rather than by specific production units. As a result, historical data had to be adjusted to reflect a theoretical first-unit cost for the purpose of developing the recurring CERs. This adjustment was accomplished by assuming a cumulative average learning curve with a 95 percent slope. Using this assumption and the number of units consecutively produced for each space vehicle program, the set of first-unit costs was obtained for use in generating the recurring cost for this CER.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 22 data points: AE, DMSP-5D1, DMSP-5D2, DSCS 4-7, DSCS 8-14, Defense Satellite Program (DSP) II 5-12, DSP 18-22, FLTSAT 1-5, FLTSAT 6-8, GPS 1-8, GPS 9-11, GPS 13-40, Intelsat IV, MARISAT, NATO3, OSO I, P72-2, P78-1, P78-2, S3, SMS 1-3, and TACSAT.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.
- **USES.** This CER estimates spacecraft cost. The spacecraft, often called the bus or platform, consists of Structure, ADCS, thermal control, EPS, TT&C, and AKM subsystems.
- **COMMENTS.** CRRES was deleted from the database used to generate this CER because it was uncharacteristically heavy for an experimental satellite.
- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. Exercise caution when estimating outside the range of the data.

- **CER**

  SC = 16.939 * SCWT, where:
  SC = First-unit cost of spacecraft in thousands of FY 92 dollars, excluding fee
  SCWT = Spacecraft weight (lbs)

- **DATA RANGE**

	SCWT
Minimum	340.3
Maximum	3063.0
Sample standard deviation	536.0

- **STATISTICS**

  Pearson correlation squared = .61
  Multiplicative error = 36%
  Degrees of freedom (SSE) = 21
  Average bias = 0%

3.30 Shroud (Payload Fairing)

The shroud CBS item includes the recurring cost of the payload shroud or fairing. This CER is based on the shroud volume in cubic inches and is described in the ACEIT methodology as follows:

- **PRODUCTION CER.** Payload fairing total direct cost (recurring).

- **DESCRIPTION.** This CER estimates launch vehicle payload fairing recurring total direct costs in thousands of FY 94 dollars, excluding overhead, general and administrative costs, cost of money, and fee. Cost is estimated as a function of payload fairing volume and total production run quantity.

  This CER estimates the lot total direct cost of the recurring hardware for whatever quantity is input into the CER.

  This CER was initially fit at the total cost level. The exponents determined for the total cost CER were superimposed on this CER. This resulted in a CER with sound form and good fit statistics.

- **SOURCE DATA.** Cost and technical data were obtained from the Atlas, Delta, and Titan System Program Offices, cost performance reports, cost data summary reports, General Dynamics Corporation, and the Aerospace Corporation at Vandenberg AFB.

  This CER is based on the following data points: Atlas IIA 11', Atlas IIA 14', Delta II 10', Titan IV 56', Titan IV 66', Titan IV 76', and Titan IV 86'.

- **REFERENCES.** “Launch Vehicle Cost Model Update,” TRI, CR-0734, 23 August 1995.

- **USES.** This CER was developed for use in estimating recurring total direct costs for launch vehicle payload fairings.

  This equation estimates an LTC for the specified quantity. It is not necessary to make ACE adjust these results for learning curve effects.

- **LIMITATIONS.** None.

- **CER**

  PLF_RTDC = 0.000046 * PLF_VOL^1.1098 * P_QTY^0.9596, where:
  PLF_RTDC = Payload fairing recurring total direct cost in thousands of FY 94 dollars, excluding cost of money, fee, overhead, and general and administrative costs
  PLF_VOL = Payload fairing volume in cubic inches
  P_QTY = Total production run quantity

- **DATA RANGE**

#OBSV		Minimum	Maximum
PLF_RTDC	7	$8,384	$92,840
PLF_VOL	7	997,14	227,017,697
P_QTY	7	3.0	20.0

- **STATISTICS**

Adjusted R-square	91.03%
Standard error (log space)	0.2394
MAD of error	18.22%
Coefficient of variation (se/mean)	19.70%

3.31 Space Vehicle Program Level

This CBS item includes the recurring cost of contractor system engineering and program management during the production phase of the program. These tend to be level-of-effort costs and somewhat responsible for the rate-based savings that can be achieved. The ACEIT documentation for this CER is as follows:

- **PRODUCTION CER.** Program level (recurring).

- **DESCRIPTION.** This USCM7 CER estimates the program-level cost in thousands of FY 92 dollars, excluding fee. Cost is estimated as a function of space vehicle total recurring cost.

  This CER estimates recurring costs associated with the effort and activity of fabricating, manufacturing, integrating, assembling, and testing of the space vehicle flight hardware. Additionally, all efforts associated with the launch and orbital operations support of a program are considered to be recurring costs.

  Contractors typically accumulate recurring program costs in total, rather than by specific production units. As a result, historical data had to be adjusted to reflect a theoretical first-unit cost for the purpose of developing the recurring CERs. This adjustment was accomplished by assuming a cumulative average learning curve with a 95 percent slope. Using this assumption and the number of units consecutively produced for each space vehicle program, the set of first-unit costs was obtained for generating the recurring cost for this CER.

- **SOURCE DATA.** Military, NASA, and commercial unmanned satellite programs are included in the database. The database has been normalized for inflation using OSD published inflation rates. All data point costs included in this CER are end-of-program actual costs or estimates of mature programs (with at least one launch).

  This CER is based on 24 data points: AE, CRRES, DMSP-5D1, DMSP-5D2, DSCS 4-7, DSCS 8-14, DSPII 5-12, DSP 18-22, FLTSAT 1-5, FLTSAT 6-8, GPS 1-8, GPS 9-11, GPS 13-40, MARISAT, Intelsat IV, NATO3, OSO I, P72-2, P78-1, P78-2, S3, SMS 1-3, TACSAT, and TDRSS.

- **REFERENCES.** USCM7 Air Force Materiel Command Space and Missile Systems Center (Directorate of Cost), August 1994.
- **USES.** This CER estimates program-level cost. The program level includes those accounts for program management, reliability, planning, quality assurance, systems analyses, project control, and other costs that cannot be related to any specific area of activity. System testing is no longer included in this area, a departure from previous editions of USCM. Program-level activities are grouped into (1) program management, (2) systems engineering, and (3) data.
- **COMMENTS.** Typically, program management accounts for 44 percent; systems engineering, 43 percent; and data, 13 percent of total program-level costs.
- **LIMITATIONS.** This CER yields an average cost for a program with average problems, average technology, an average schedule, and average engineering changes. Exercise caution when estimating outside the range of the data.
- **CER**

  PL = 0.252 * SVREC, where:
  PL = First-unit cost of program level in thousands of FY 92 dollars, excluding fee
  SVREC = Space vehicle total recurring cost (spacecraft + communications + IA&T) in thousands of FY 92 dollars, excluding fee

- **DATA RANGE**

	SVREC
Minimum	13,696.3
Maximum	987,174.6
Sample standard deviation	215,140.9

- **STATISTICS**

  Pearson correlation squared = .83
  Multiplicative error = 39%
  Degrees of freedom (SSE) = 23
  Average bias = 0%

3.32 Production Ground User Equipment

This CBS item includes the recurring production cost of the ground mission equipment. Because this cost is very mission dependent, no methodology was implemented for this item. It must be estimated on its own and entered into the ground portion of the Input screen (a passthrough). The general estimating approach should take into account the type of user equipment and the number of sets. There are a number of models suitable for estimating ground communications equipment, from large wideband dish antennas and receivers to handsets. Many of these are embedded in ACEIT’s CER library. The Cost Panel recommends developing this passthrough estimate at the same time as the ground software and ground user equipment development estimates.

For the purpose of the SBR trial case, we assumed there would be common datalink compatible communications equipment with processing workstations integrated into existing image processing facilities with 25 units. We estimated that this equipment would cost approximately $1 million (1992) per unit, including spares.

3.33 Production Fee

The production fee item includes all the direct profit or fee in the production phase of the program. It is estimated as a cost-on-cost factor, with the rate specified by the user in the Management area of the Input worksheet. The base this factor is applied to is the sum of the space vehicle PME, the ground user equipment, and the program level. A fee rate of 10 percent was used in the production phase.

3.34 Government Production Other Costs (SPO Only)

The methodology is the same as described above for EMD government costs, and is used only if development has ceased; otherwise, these costs continue to be carried in the equivalent EMD line.

3.35 O&S Mission Personnel

The O&S mission personnel item includes the O&S cost for the personnel who will perform mission-related functions (not fly the satellite). The model estimates this cost on a per-deployed-unit basis per year of O&S. For the trial case of the SBR constellation, we assumed that 10 people per deployed unit would be required, with 25 units being deployed, and that the average rate per person is $100,000 (1998) per year.

3.36 O&S Personnel (SOC)

The O&S personnel (SOC) item includes the fully burdened O&S cost for the personnel who will perform satellite control and telemetry and tracking functions (fly the satellite). For the SBR trial case, we obtained an actual representative cost for an SOC, which was $10.4 million (1995) per year.

3.37 O&S Mission Equipment Maintenance

The O&S mission equipment maintenance item accounts for the O&S costs that maintain the mission equipment. It is estimated as a percentage of the total recurring mission equipment cost. The percentage is entered by the user in the ACE Exec Input worksheet. There are two percentages. The first is an annual maintenance percentage. We assumed 10 percent for this. The second is an upgrade percentage, which occurs periodically after a certain number of years specified by the user. We assumed 50 percent for this percentage and an upgrade period of 7 years.

3.38 O&S Equipment Maintenance

Similar to the mission equipment, the O&S operations equipment maintenance item accounts for the O&S costs of maintaining operations equipment. It is estimated as a percentage of the total recurring mission equipment cost. The percentage is entered by the user in the ACE Exec Input worksheet. There are two percentages. The first is an annual maintenance percentage. We suggest 10 percent for this. The second is an upgrade percentage, which occurs periodically after a certain number of years specified by the user. We recommend 50 percent for this percentage and an upgrade period of 5 years.

3.39 O&S Other Government Costs (SPO Only)

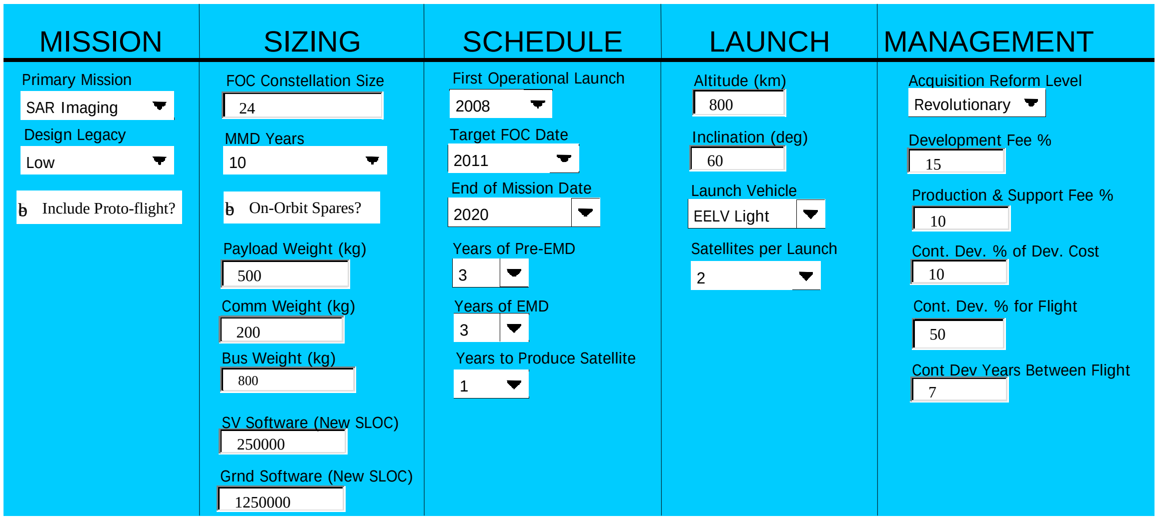
The O&S other government costs (SPO only) item accounts for the program office personnel costs in the event that there is no SPO funding for development or production activities while the system is being operated. In the context of this model, this will occur only at the very end of the program life cycle. Other than this, the methodology is the same as that used for the EMD and production phases.

3.40 The Excel Workbook

The estimating methodologies described in the previous section were implemented in ACEIT. ACEIT requires training (approximately 1 week) to use it for estimating and to understand its output. To shield this complexity from the novice user and facilitate the utility of the model, we constructed a Microsoft Excel front end and back end to the ACEIT model. This was implemented through an Object Linking and Embedding facility of ACEIT called the "ACE Executive." This series of spreadsheets not only facilitates the collection of inputs, but also preprocesses some of the inputs and does some consistency checking. Finally, it collects and formats the results. The following paragraphs briefly describe each of the Excel worksheets and its function.

3.41 Input

The Input worksheet is the user interface for supplying a general description of the program to be estimated. Figure A-1 shows the input dialog portion of this sheet. This input screen is organized as several sections containing a number of text boxes and drop-down choice lists. As the user specifies these input parameters, the values may be processed and checked in the portion of this worksheet below the blue input area. The values are then sent to the Time Phased worksheet where they will be passed into ACEIT, and if they affect the launch schedule, they may also be used to derive the time phasing of the launches.



MISSION

Primary Mission: SAR Imaging
Design Legacy: Low
☑ Include Proto-flight?

SIZING

FOC Constellation Size: 24
MMD Years: 10
☑ On-Orbit Spares?
Payload Weight (kg): 500
Comm Weight (kg): 200
Bus Weight (kg): 800
SV Software (New SLOC): 250000
Grnd Software (New SLOC): 1250000

SCHEDULE

First Operational Launch: 2008
Target FOC Date: 2011
End of Mission Date: 2020
Years of Pre-EMD: 3
Years of EMD: 3
Years to Produce Satellite: 1

LAUNCH

Altitude (km): 800
Inclination (deg): 60
Launch Vehicle: EELV Light
Satellites per Launch: 2

MANAGEMENT

Acquisition Reform Level: Revolutionary
Development Fee %: 15
Production & Support Fee %: 10
Cont. Dev. % of Dev. Cost: 10
Cont. Dev. % for Flight: 50
Cont Dev Years Between Flight: 7

Figure A-1. *Main Input Screen*

The first area of the Input worksheet asks the user to choose a mission type. The mission type determines both the cost in thousands of FY 92 dollars per pound of the payload and the payload annual percent reduction as described above. Table 1 above shows the annual percent reductions of payload cost by mission type.

The cost per pound will be multiplied by the payload weight entered into the Sizing area of this worksheet, and the annual percentage reductions will be applied until the first year of production, as determined by the schedule inputs. It should be noted that the costs per pound were based on very limited data, and these values will be updated in future versions of this tool.

The next choice requested is the design legacy. Design legacy represents the extent to which the program being estimated is like a previous program so as to reduce the amount of development effort. There are three choices here: low, medium, and high. A low design legacy should be selected for any clean-sheet design or unique systems. The effect of this choice is to determine the ratio between the nonrecurring development cost incurred during the EMD portion of the program and the recurring production cost of the payload (theoretical first-unit cost or “T1”). Selecting a low design heritage causes this ratio to be 4. A medium design legacy should be selected for programs with significant similarities to previous programs; this will invoke mature technologies, and integrate primarily off-the-shelf components. In this case, the payload nonrecurring development cost to recurring production cost ratio is 2.5. A high design legacy should be chosen when the program involves only a minor modification or an upgrade to a previously developed program. Furthermore, it is assumed that the prime and major subcontractor relationships remain the same. In this case, the nonrecurring development cost to recurring production cost ratio is one to one, which means that the development cost essentially amounts to the T1 cost for the prototype.

This brings us to the next input, which allows one to specify whether there will be a prototype. In most cases a medium or low design legacy program will include a prototype in the development program. Therefore, the default is to have a prototype. The most likely reason one would choose not to have a prototype is if the design legacy is high and there is no need for a prototype. Deselecting the prototype box reduces the ratio of nonrecurring development cost to recurring cost by one T1, or the cost of a prototype. This is particularly useful for nondevelopmental items or commercial systems where there is no need for a prototype, or where the prototype will count against the operational constellation size. When the prototype box is deselected (no prototype), the nonrecurring to recurring ratios for low, medium, and high become 3, 1.5, and 0 respectively.

The first item requested in the Sizing area is the final operational constellation size. This is the number of satellites required to be operational simultaneously, excluding any on-orbit spares. The number of on-orbit spares is calculated by the model, based on the constellation size and the mean mission duration (MMD), which is the second parameter requested. In general, the larger the constellation and the shorter the MMD, the more on-orbit spares will be required. The MMD list box is arbitrarily limited to 12 years, but typical values range from 5 to 10 years depending on the mission, the design margins and redundancy, and the orbit (lower orbits being more stressing). All of these inputs, along with the dates and durations in the Schedule area of this worksheet, will determine the number of satellites produced and launched over the program’s life cycle.

There are three weights requested in the Sizing area. The first is a payload weight estimate, which will be multiplied by a cost per pound (determined by the mission type) to generate a T1 payload cost. The second weight requested is for any wideband mission data communications equipment (not TT&C equipment). A USCM7 weight-based CER is applied to this weight to calculate a T1 cost. The third weight request is for the spacecraft bus, which would include the weight of structures, thermal, attitude determination and control, electrical power, propulsion, and TT&C communications equipment. The bus is also estimated with a USCM7 CER. All the estimated costs are de-escalated at various rates from 1992.

At the bottom of the Sizing area of the worksheet is a request for a software size estimate in SLOC for both the space and ground software. This size estimate will be multiplied times a de-escalated cost per SLOC to get the software development cost. It should be assumed that the software size estimate is the effective new SLOC. Therefore, if reuse and commercial off-the-shelf are being considered, the size of the SLOC estimate should be reduced appropriately.

The next area of this worksheet requests dates and durations associated with the schedule of the program, including the first operational launch date, which is also the initial operational capability (IOC) date, the full operational capability date, and the end of mission (EOM) date. It also requests the year(s) duration of pre-EMD, EMD, and the time it takes to produce a satellite. This information is used to calculate the program schedule. Some of this information is used in the Launches worksheet to determine the schedule of launches and recurring production. All of the schedule information is then used in ACEIT to phase the cost estimate over time. The phased results are calculated in ACEIT and returned to the Time Phased worksheet. A stacked bar chart of the cost estimate, by acquisition phase over time, is presented in the Sand Chart worksheet.

The next area of the Input worksheet requests information about launch. The first two input boxes request the orbit altitude in kilometers and the inclination in degrees. These values are used to adjust the weight-constrained payload capacity of the various launch vehicle alternatives, based on a curve fit of specific calculated values. This curve fit is not precise, but it is intended to constrain the reasonable options available for launch. Detailed analysis would be necessary to confirm the viability of a selected launch option. Once the payload weight and orbit altitude and inclination are specified, one can choose from a list of potential launch vehicle alternatives, and if the weight-constrained launch capacity allows, one can choose to stack multiple satellites on each launch vehicle (a common practice). For example, in the SBR trial case, we selected an EELV Light launch vehicle, which had the weight capacity to launch two SBR satellites at the same time.

The selection of launch vehicle has several effects on the cost estimate. Obviously, it affects the cost of the launch vehicle. However, it also affects the speed at which a constellation can be constituted because of a constraint on the number of launches per quarter. This logic is discussed in the description of the Launches worksheet in Section 3.43.

The next area of the Input worksheet, not yet designed or implemented, is the Operations area. In future versions of this tool, this area will contain requester boxes for the operations-related inputs, which currently must be entered into the Time Phased worksheet. The information requested will include the number of mission ground equipment sets purchased, the cost of these equipment sets, the number of operational units with which the equipment is deployed, and the staffing per operational unit with which the mission equipment is deployed. There will also be questions about the SOC that performs the ground TT&C functions.

The last area in the Input worksheet addresses the management approach and costs. The first and most important question is how aggressively program management will adopt reforms that could reduce cost. The most pessimistic choice, “traditional,” assumes that business is conducted as it was circa 1992—the time frame of the data from which the USCM7 CERs were developed. This level nullifies the annual cost-reduction percentage and specifies a large, conventionally sized SPO. The rationale for including this option is to give the user a good indication of the estimate one might derive from traditional cost-estimating methods, and to give a baseline for the magnitude of potential savings when adopting more aggressive management approaches. The second option, “reformed,” results in half of the annual percentage reductions that can be achieved by adopting a “revolutionary” approach, and also results in an SPO smaller than the traditional approach, but larger than a revolutionary approach. The user is warned that the effects of this selection are meant to be advisory only, and not to provide an estimate of the quantitative effects of specific management changes (which are not specific) that would result in these savings. Providing the later accurately would require an enormous longitudinal cost research effort, and it is not clear that such research would ever keep pace with changes in acquisition policy and management science. The full intent of including this option was to show that business as usual will result in historically predicted costs, and that reaping the cost savings created by the commercial sector will likely require revolutionary changes in acquisition policy and management approaches. The definition of “revolutionary” then becomes doing whatever is necessary to take full advantage of possible savings due to the expanding commercial market.

3.42 Cost Assumption Worksheet

The Cost Assumption worksheet has only one area as of this writing, although we would like to expand it to include all passthrough estimates and factors. As described above, the pre-EMD estimate is a passthrough, and this area is where information is entered. The software cost (1992 dollars per SLOC) for both flight and ground software is also entered here.

3.43 Launches Worksheet

The Launches worksheet calculates the number of launches per quarter, if any, that are necessary to constitute and maintain the constellation of satellites, given the schedule values and the launch vehicle selected in the Input worksheet. In general, the first operational launch date is entered first, then the fully constituted constellation size, including any on-orbit spares, and finally the number of launches that can take place in a single quarter. The worksheet then calculates for each quarter how many, if any, launches are necessary and possible. It uses a very trivial formula based on the satellite MMD and the number of satellites on-orbit to calculate the number of satellites that will fail in each year. It will schedule launches as necessary until the EOM date to maintain the constellation. It also calculates, based on the time it takes to produce a satellite, when production must commence to meet the launch dates. Finally, yearly totals of satellites produced and launched are tallied in the upper right-hand rows of the worksheet. These totals are then sent to the Time Phased worksheet where they are passed to the ACEIT session, ultimately affecting the time phasing of the cost estimate.

The Launches worksheet is intended to give high-level insights into the required launch schedule and the associated cost-phasing implications. It is not intended as a substitute for specialized availability and schedule modeling, such as the Generalized Availability Prediction Program analysis or production and launch schedule network analysis. The availability and schedules would in reality be affected by many factors not modeled here, including launch schedule conflicts with other systems, production and launch delays, production capacity limitations, optimal production facility utilization, and funding availability. The schedules generated here should be considered ideal and probably unrealistic. This weakness can be compensated for by entering more realistic dates and durations into the Schedule area of the Input worksheet.

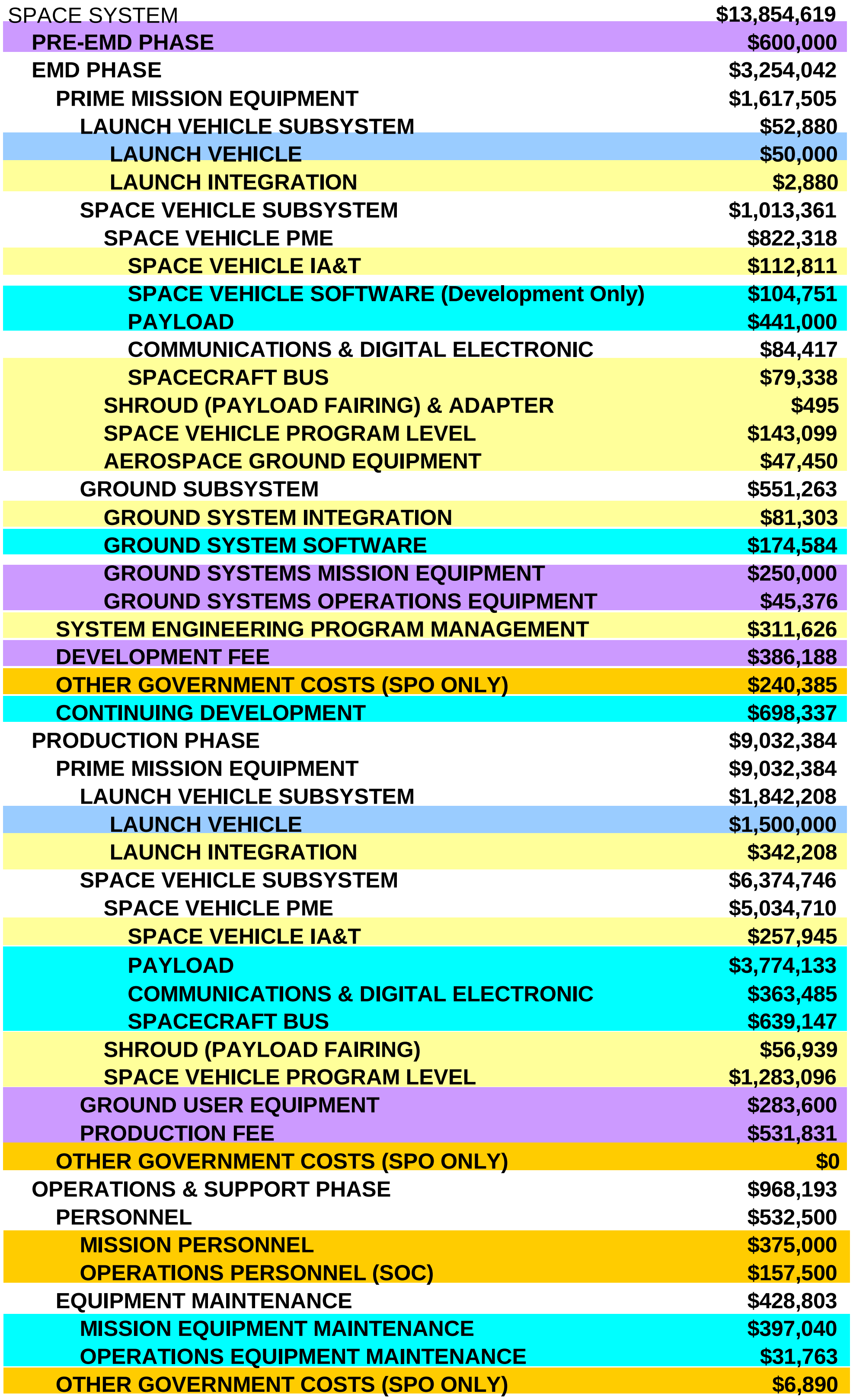
3.44 Time Phased Worksheet

The Time Phased worksheet acts as the interface between Excel and ACEIT. Using an ACEIT feature called “ACE Executive,” data is passed to and from Excel and ACEIT. The upper vertical rows of this worksheet are occupied by the CBS items, with the total and the annual values for each CBS item in subsequent columns to the right. The lower vertical rows are occupied by various input parameters. For consistency with the Cost Details worksheet, the CBS items have been color-coded by estimating methodology type.

Note: It is essential that the session file name in the upper left-hand corner match the location of the ACEIT session with which the Excel file is associated. For our trial case, the ACEIT session name was testarch.acw, and it was located in the e:\sab\ directory. By pressing the “Session…” button second from the left at the top of this worksheet, users can specify the location of the associated ACEIT file. We recognize that users may want to modify this worksheet and/or the ACEIT file. To avoid undue frustration, novice users should be aware that ACE Executive is an advanced ACEIT feature that should be approached with patience and some previous ACEIT experience. Particularly vexing is the conversion of dates between ACEIT and Excel, but there are other more subtle challenges that can decrease the efficiency of modeling efforts. To minimize these difficulties, TRI offers periodic ACEIT training for all levels. We strongly recommend basic ACEIT training as a prerequisite for modifying the ACEIT session or the interface between this Excel worksheet and the ACEIT session. Inquiries about training should be directed to Mr. Darren Elliot of TRI's Santa Barbara office at (805) 964-6963.

3.45 Cost Details Worksheet

The Cost Details worksheet (Figures A-2 and A-3) shows the cost totals (in thousands of FY 98 dollars) of the Time Phased worksheet and provides a pie chart (Figure A-3) of the distribution of the costs by cost-estimating methodology type. The pie chart should provide the user with a sense of the relative importance of the five methodology types used in this model. For the case of the SBR, the largest portion, representing nearly half the estimate, is the de-escalated dollars per pound. Formal CERs, which have been officially approved by SMC and, in most cases, the Air Force and OSD Cost Analysis Improvement Groups, are used to estimate the second largest portion of the cost. The rough order-of-magnitude cost estimate for the EELV together with other passthroughs makes up about a quarter of the estimate. Man-loading was multiplied by rates to estimate the remainder of the cost, most of this in O&S.



SPACE SYSTEM	$13,854,619
PRE-EMD PHASE	$600,000
EMD PHASE	$3,254,042
PRIME MISSION EQUIPMENT	$1,617,505
LAUNCH VEHICLE SUBSYSTEM	$52,880
LAUNCH VEHICLE	$50,000
LAUNCH INTEGRATION	$2,880
SPACE VEHICLE SUBSYSTEM	$1,013,361
SPACE VEHICLE PME	$822,318
SPACE VEHICLE IA&T	$112,811
SPACE VEHICLE SOFTWARE (Development Only)	$104,751
PAYLOAD	$441,000
COMMUNICATIONS & DIGITAL ELECTRONIC	$84,417
SPACECRAFT BUS	$79,338
SHROUD (PAYLOAD FAIRING) & ADAPTER	$495
SPACE VEHICLE PROGRAM LEVEL	$143,099
AEROSPACE GROUND EQUIPMENT	$47,450
GROUND SUBSYSTEM	$551,263
GROUND SYSTEM INTEGRATION	$81,303
GROUND SYSTEM SOFTWARE	$174,584
GROUND SYSTEMS MISSION EQUIPMENT	$250,000
GROUND SYSTEMS OPERATIONS EQUIPMENT	$45,376
SYSTEM ENGINEERING PROGRAM MANAGEMENT	$311,626
DEVELOPMENT FEE	$386,188
OTHER GOVERNMENT COSTS (SPO ONLY)	$240,385
CONTINUING DEVELOPMENT	$698,337
PRODUCTION PHASE	$9,032,384
PRIME MISSION EQUIPMENT	$9,032,384
LAUNCH VEHICLE SUBSYSTEM	$1,842,208
LAUNCH VEHICLE	$1,500,000
LAUNCH INTEGRATION	$342,208
SPACE VEHICLE SUBSYSTEM	$6,374,746
SPACE VEHICLE PME	$5,034,710
SPACE VEHICLE IA&T	$257,945
PAYLOAD	$3,774,133
COMMUNICATIONS & DIGITAL ELECTRONIC	$363,485
SPACECRAFT BUS	$639,147
SHROUD (PAYLOAD FAIRING)	$56,939
SPACE VEHICLE PROGRAM LEVEL	$1,283,096
GROUND USER EQUIPMENT	$283,600
PRODUCTION FEE	$531,831
OTHER GOVERNMENT COSTS (SPO ONLY)	$0
OPERATIONS & SUPPORT PHASE	$968,193
PERSONNEL	$532,500
MISSION PERSONNEL	$375,000
OPERATIONS PERSONNEL (SOC)	$157,500
EQUIPMENT MAINTENANCE	$428,803
MISSION EQUIPMENT MAINTENANCE	$397,040
OPERATIONS EQUIPMENT MAINTENANCE	$31,763
OTHER GOVERNMENT COSTS (SPO ONLY)	$6,890

Figure A-2. *CBS Color Coded by Methodology From Cost Details Worksheet (SBR System)*

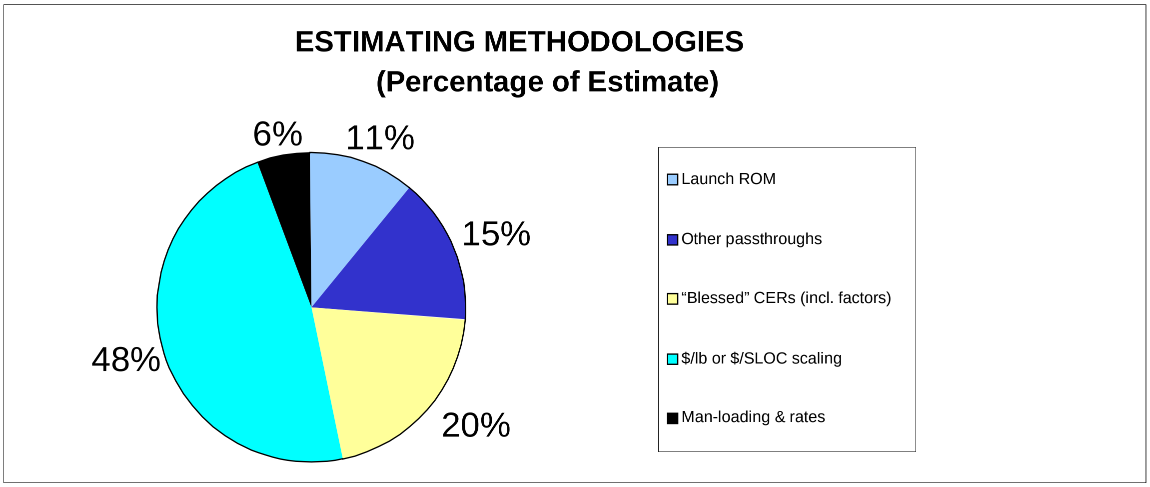


Figure A-3. *Methodology Color Code for Figure A-2 From Cost Details Worksheet*

The user should view these percentages with caution. It is very unlikely that the estimates from this model could be used as the basis for even a DoD Acquisition Milestone I Approval. The costs per pound and cost per SLOC, used to estimate the largest fraction of the cost and to which many of the other factors are applied, have not been validated over a large enough database of systems. Furthermore, the costs per pound and per SLOC are crude, merely allowing estimates of systems that are insufficiently defined for estimation by more conventional methodologies.

3.46 Sand Chart Worksheet

The Sand Chart worksheet contains a graph of the time-phased cost estimate, by acquisition phase. The intent of this graph is to give a manager a sense of the peak funding and the duration of funding required to execute a program, as well as a relative sense of the costs of the various acquisition phases. This view can also be useful in deciding how to schedule the program to smooth peaks and even out costs.

3.47 Limitations and "To Do" Items

There are many improvements still required to make this model as capable as it was intended to be. The first and most important of these improvements is to collect additional data to confirm or modify the cost per pound for the various payload types and analyze commercial space system data that would confirm or challenge the cost de-escalation that is at the heart of our methodology. This is the single largest driver in the model, and it deserves more consideration.

More default and choice or option lists must be developed for the input screen. Ideally, these choices would allow one to begin with a variety of preloaded satellite alternatives which would set all input parameters. One could modify these values from these starting points.

Some input parameters must still be entered directly by the user into the Time Phased worksheet rather than the Input worksheet. Furthermore, the units on these inputs are not well documented. All of the model inputs should be entered from the Input worksheet, and the cells in which they are entered must be named appropriately to avoid the confusion of a worksheet and cell reference otherwise used by Excel.

In the launch vehicle selection choice lists, we provide a minimal level of engineering checking by limiting the launch vehicle choices based on the satellite weight and the selected orbit. The purpose of this checking is to provide guidance to the user. There are many areas of the model that could be enhanced with this kind of checking.

Finally, it would be useful to populate the model with a series of consistent input parameters based upon a user selection from a list of historical systems. These parameters could be used as known anchor points for the specification of future systems.

3.48 Estimated Systems

3.48.1 STARLITE-Like Space-Based Radar

The Cost Panel decided in March 1998 that it would be prudent to exercise our planned approach against a trial architecture. By April 1998, it became clear that the other SAB panels were not prepared to provide the Cost Panel with a trial architecture or even a system. As a substitute, the panel developed its own trial system. The system was a distributed constellation of SBRs capable of GMTI and 1-meter-resolution-class SAR. The Cost Panel chairman suggested a nominal description of the system, and the other Cost Panel members augmented the description and were assigned to poll the other panels for comments. Eventually, it was determined that the system was very similar to the ongoing STARLITE program (now Discoverer II) being managed by DARPA. The concept definition studies for this program had already produced the technical inputs that we required to try out our cost models. We collected those program description and technical inputs from Dr. Jeffrey. After these discussions, a few additional input parameters were required, most notably a software sizing that had not been completed. It should be mentioned that the average unit cost of the space vehicles agreed very well with the DARPA supposition of $100 million per satellite. This program, adopted as our trial case, was the only program fully endorsed by the Summer Study for development work beyond studies and technology development.

3.48.2 Ground-Based Laser

We were directed to include an $8 billion cost estimate of a GBL system with a 25-satellite constellation of relay mirrors and two ground laser sites (approximately 60 satellites required over a 10-year operational life with a 5-year MMD). Since we were not told the year dollars for the estimate, we assumed it was 1992 constant-year dollars. For security and other reasons, no technical or programmatic detail of this system was provided other than an IOC date of 2005 and an EOM date of 2015. Given the large, early, and uncertain funding required to pursue such a concept, the study recommended continued development of technology supporting affordable lightweight optics.

3.48.3 Highly Operable Space Vehicle

A number of variants of a maneuverable and rapid-response launch system were discussed during the study. We were told that the AOV had a 12,000-pound reusable and unmanned airframe (dry weight), and a 2,000-pound payload, and was launched by a GFE booster. The IOC date that was initially provided was 2012 but was later changed to 2016 in order to avoid a peak in the budget projections because the peak of the development costs would overlay the peak in the SBR production costs. Based on this description, we were asked to provide a cost estimate. Commensurate with the detail provided and Space Shuttle experience, we estimated the airframe at a T1 cost of $1,000,000 (1992) per pound, leading to a T1 cost of $1.2 billion. No de-escalation was taken due to the probable lack of commercial interest in such a launch concept. As this system would be a completely new development, a nonrecurring cost-to-T1 cost ratio of 4 was applied, leading to a development cost of $4.8 billion. Four vehicles were slated for purchase beyond the prototype, one per year, on a 95 percent cumulative average learning curve.

3.48.4 A Comment About Distributed Laser Communications Costs

In the course of the study, the Payloads Panel proposed a wideband (5 gigabits per second [Gbps])-distributed laser communications approach. The capability provided would relieve the data rate constraint on area rate and resolution of imaging systems, and would replace relatively large and expensive gigabit-class RF systems that are approaching the limits of technology. No specific system description was brought to the Cost Panel for estimating, but we based our estimate on the idea that at least three geostationary earth orbit (GEO) communications relays and all wideband low earth orbit imaging systems would be equipped with 5-Gbit laser cross-links with 30-centimeter (cm) class optics and 1-micron lasers of roughly 5 watts. The GEO satellites could perhaps be commercial platforms. Other than to note that the pointing requirement of such a system is similar to Space-Based Infrared System-Low, we suggest that the proposal, if feasible, would replace the substantial weight and cost of wideband radio-frequency communications. The Payloads Panel suggested that each payload would cost roughly $10 million. If so, the cost savings would be substantial. However, a quantification of those savings would require a description of the proposed RF system to be replaced, as well as a quantity and schedule for the procurement of this capability. Since these things remained undefined, the Cost Panel, declined to estimate the cost or savings. One can get a general sense of the magnitude of potential savings for the proposed distributed constellation of SBRs. Each of the 60 SBRs to be built would be equipped with a 4X common datalink, approximately 1 Gbps direct downlink. Given our assumed aggressive de-escalation of communications equipment prices (6 percent per year from 1992), these downlinks average roughly $6 million (then year) each. While it may be difficult for a 30-cm laser communications payload to beat this price, it may justify itself with increased data rate, greater operation flexibility, and weight savings. It is also possible that the projected cost reductions of RF communications will not materialize or will flatten out at some point.

4.0 Budget Projections and Planning

Another major task for the Cost Panel was to project the unclassified Air Force space and intelligence, surveillance, and reconnaissance (ISR) aircraft budget into the future while considering the cost of proposed new systems and possible savings. The purpose of this exercise was to quantify budget constraints on future plans, constraints that were qualitatively understood as meaning no real increase in budget authority. As a point of departure, we created a Microsoft Excel spreadsheet of the 14 January 1998 PB for space program elements and ISR aircraft programs out to 2003. The aircraft (Joint Surveillance, Target, and Attack Radar System, Airborne Warning and Control System, U-2, and various unmanned aerial vehicles) were included because of the desire to consider missions and architectures across the systems that accomplished them. The spreadsheet was organized around the identified architectures: infostructure, navigation, meteorology, launch, ISR/warning, force application, and infrastructure, which included satellite operations, ranges, and leadership and support program elements. Beyond 2003, the budgets were essentially flatlined, assuming a constant 2.2 percent inflation rate of then-year dollars. This baseline was maintained as a separate worksheet and mapped into all subsequent options. There were several large program elements that were not flatlined from 2003 because of known reductions and terminations of activities. Among these were Milstar, EELV, and Gapfiller. We also added a budget line to the baseline in the infostructure architecture for terrestrial-based communications (landlines). This roughly $60-million-a-year estimate came from a study done for the Office of the Space Architect.

The initial hope of developing a family of alternative architectures was made futile by the time limitations on the study. The architectures gave way to a set of options sketched out by the study director. While as many as five options were initially considered, by the end of the study only three options were presented and just one recommended. The first of these options (baseline plus) was the baseline as described above plus the three future systems—SBR, GBR, and AOV. Given budget constraints, that option was clearly not viable. The second option (aggressive reductions) included the new systems and severely reduced operating costs, relying almost exclusively on commercial communications, and rapidly terminating or transferring a large number of current activities, including military satellite communications (MILSATCOM), launch, and range support. The third option (moderate reductions) was to dramatically reduce operating costs while transferring the majority of responsibility for communications and range activities to commercial entities. The following paragraphs will describe these three options.

Each option used the 14 January 1998 PB as a starting point. We would have preferred to use the Program Objective Memorandum (POM), because the PB went out to only 2003, whereas the POM went out to 2005. We extended the budget from 2003 in most cases by applying a 2.2 percent inflation rate each year until 2020, the agreed-to end date for our financial analysis. There were exceptions to this logic. SAF/AQS[11] personnel (Cost Panel members), having interacted with many of the space PEMs, were aware of specific program schedule and budget issues captured in the out years of the POM yet not captured in the PB. In those cases, the budgets were adjusted (in every case downward) in 2004 and 2005 before being escalated at 2.2 percent into the future. Those reductions are the source of the slight dip in 2004 and 2005 before the smooth increase in the budget due to inflation. Specifically, MILSATCOM, Ultrahigh Frequency Follow-On, and EELV were decreased in line with POM projections. This baseline is shown in Figure A-4.

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[11] Assistant Secretary of the Air Force, Acquisition, Space and Nuclear Deterrence.

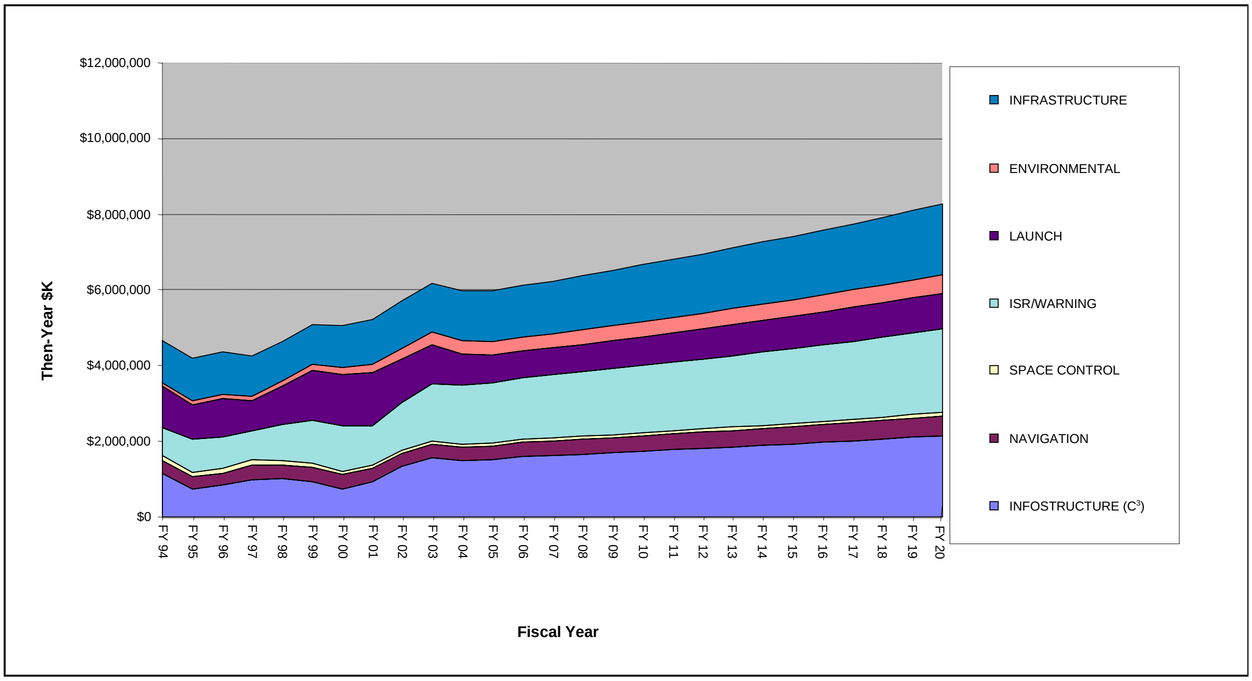

Figure A-4. *Budget Baseline*

Baseline plus (Figure A-5) included the three new systems: a GBL, an SBR, and an AOV. The estimates for these are described in the previous section. These are order-of-magnitude estimates and are not suitable for regular budget planning. At a rough level, after a decision to delay the AOV, these systems were scheduled in order, following each other by approximately 5 years. At the request of the study director, the annual funding levels for these systems are aggregated into one account described as “new programs” in the study findings. The sum of these new programs quickly grows to more than $2.6 billion (then year) per year by 2006 and averages $2 billion from FY 01 to FY 20, for a total over 20 years of $41 billion, peaking at $3 billion in FY 15. These new programs would require the portion of the budget considered to expand by an average of roughly 5 percent each year from FY 00 to FY 06. The Cost Panel believed that having so many new programs is unrealistic. Therefore, only options including one or two of the new programs and substantial reductions of other budget lines could be seriously recommended. For example, including only the SBR requires the budget under consideration to be increased $16.7 billion or 8 percent on average over 20 years, with a peak of $1.7 billion in FY 07. It should be noted that the Cost Panel’s role in this bounding decision was perhaps our largest contribution to the study.

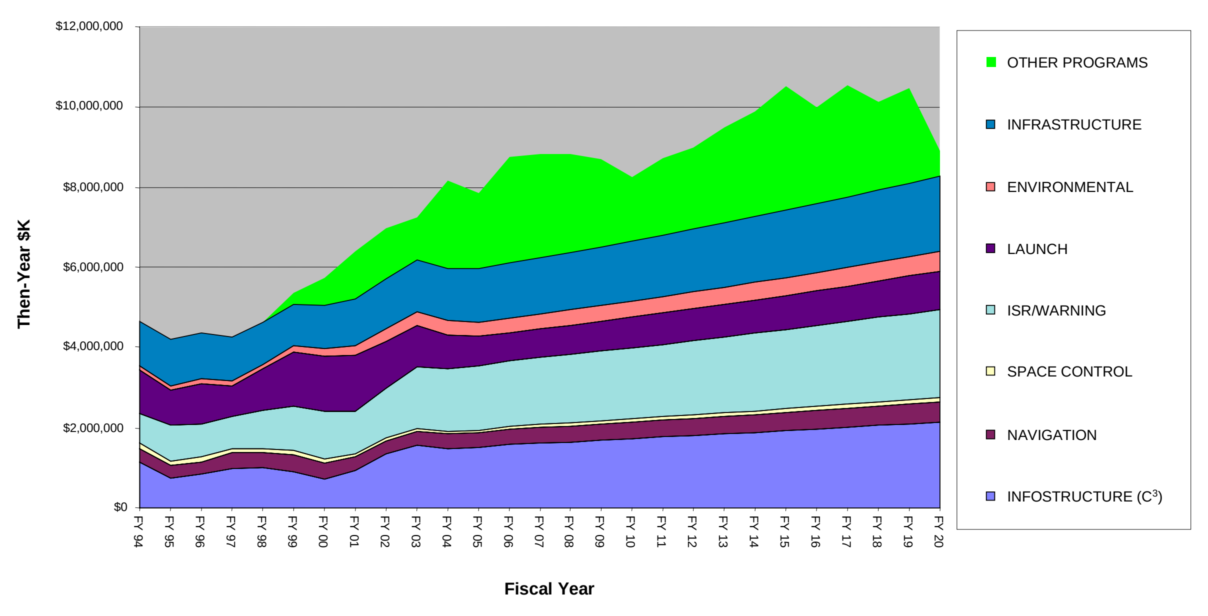

Figure A-5. *Baseline Plus New Programs*

Much of the Cost Panel's effort was concentrated on identifying savings that could be achieved by more efficiently acquiring, launching, and operating systems. There was also serious consideration of transferring and eliminating certain activities not central to the mission of an aerospace force, calling such reductions "divestiture." The remaining two options took different approaches to quantifying potential savings.

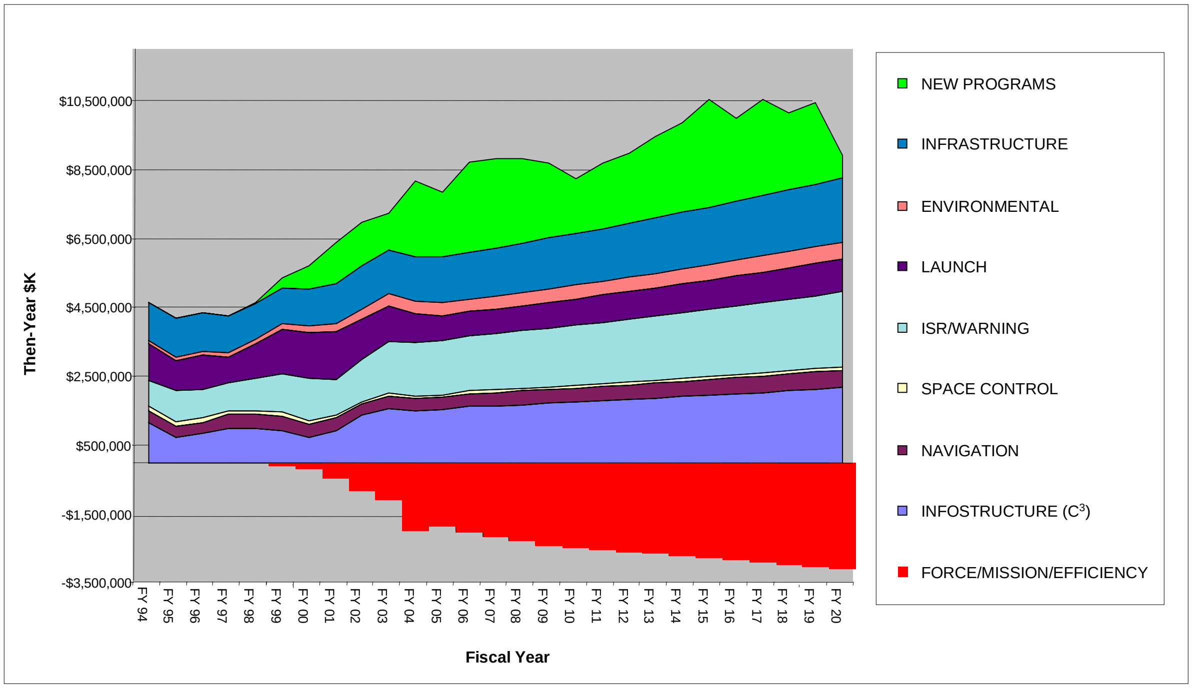

Figure A-6. *Aggressive Reductions Because of Force and Missions Reductions and Efficiencies*

The “aggressive reductions” option (Figure A-6) led by the Operations Panel started with the baseline-plus option and reduced, eliminated, or transferred responsibility for all activities not central to warfighting from space. As Figure A-6 shows (for Force/Mission/Efficiency), the substantial savings off the baseline begin as early as FY 01 and quickly reach $2 billion per year in 2004. Between FY 01 and FY 20, total savings exceed $45 billion, averaging $2.3 billion per year.

Everyone was well aware of the political and management challenges of making such draconian reductions, especially in the near future and where the Air Force has commitments to the other branches of the armed services. For example, hundreds of millions of dollars have been invested in Milstar terminals deployed throughout the military. Any reduction or elimination of Milstar service would require additional investments to continue to provide equivalent capability. Furthermore, it is not certain that another government agency or commercial entity would be interested in accepting the transfer of missions, assets, and requirements. An example of this is the launch operations of the Eastern and Western Space and Missile Centers. In effect, the Air Force currently subsidizes commercial and civil launches from these facilities by charging only the marginal cost of additional launches. The full cost of operating these facilities, evenly allocated to all users, would be many times what is currently charged and prohibitively expensive for many users. It is difficult to envision a commercial scenario that would be profitable without similar subsidies through other channels that might not be as politically compelling as military access to space. The aggressive reductions option was therefore presented as an ideal that could be reached for but not implemented.

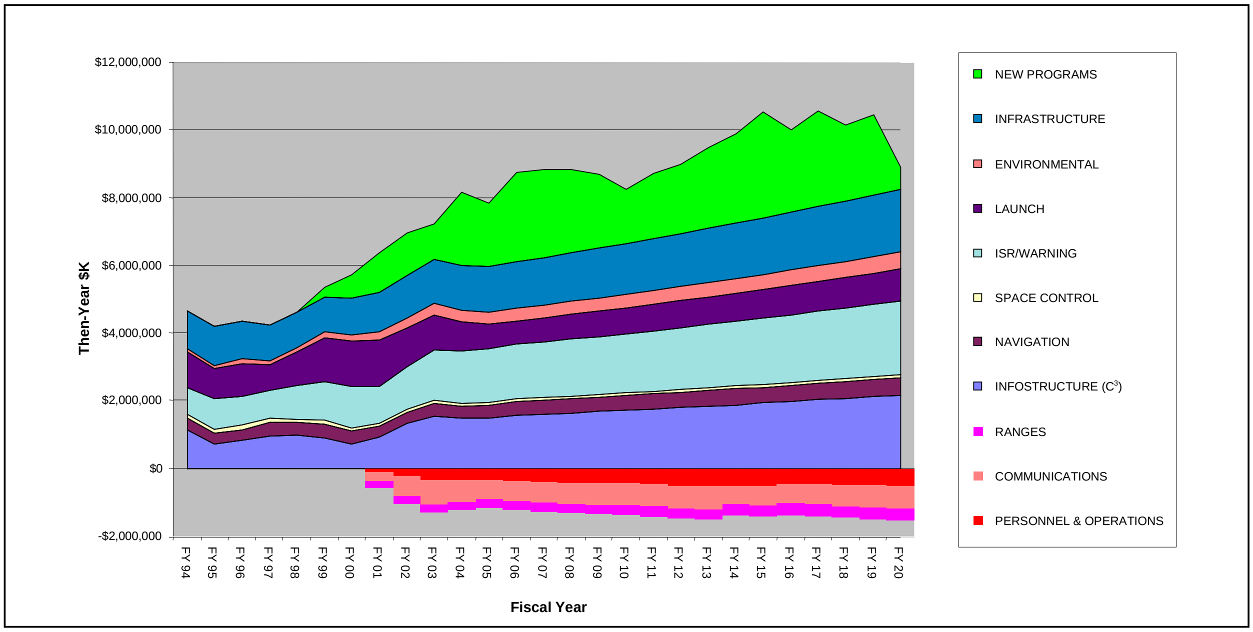

Figure A-7. *“Moderate Reductions” to O&M and MILPERS Accounts, Communications, and Ranges*

The moderate reductions (Figure A-7) option was an attempt by the Cost Panel to identify aggressive but realistic reductions in a limited number of areas. The three areas targeted were communications, O&S (including military personnel), and range operations. In the communications area, almost all programs are phased out except a portion of the MILSATCOM budget preserved in good faith to current users. Some of this cost is put back in a wedge for commercially leased communications. All operations and maintenance (O&M) costs and military personnel (MILPERS) costs were reduced 30 percent, decreasing by 10 percent per year starting in FY 01. By 2003, this amounts to a savings of more than $360 million (then year), and averages 5 percent of the budget in subsequent years. These savings were designed to reflect general process improvement and consolidation of support functions. Finally, the O&M and MILPERS costs associated with the ranges are reduced to just 20 percent of their baseline values by FY 03, and all investment is eliminated, reflecting a transition to a “national range” approach for launch infrastructure. Each of these reductions must be studied thoroughly to assess its feasibility. From FY 01 to FY 20, savings from these reductions in range costs average just over 3 percent of the baseline budget being considered.

The savings from the moderate reductions option are sufficient to offset only two-thirds of the increases estimated to be required by the new programs. For example, the then-year cost of the SBR program is $16.7 billion from FY 01 through FY 20. Savings in the moderate reductions option total more than $27 billion over a similar time frame. Therefore, the “moderate reductions” option is consistent with the objectives and recommendations of the Summer Study.

5.0 Lessons Learned

The 1998 SAB Summer Study was the first Summer Study to include a Cost-Estimating and Acquisition Strategy Panel. As with any new endeavor or tool, more was learned about what could have been done better than was actually accomplished. One of the objectives of the study was to leave a legacy of processes and tools behind for future studies. We hope to partially fulfill that goal in this section as we summarize our recommendations to improve the Cost Panel support to future SAB studies.

- The study director should send out a call for system concepts 3 months prior to the general Summer Study meeting and establish a deadline of 2 months prior for responses. In this call, the director should provide a form or questionnaire that solicits information sufficient for cost estimating.

  The Cost Panel's support to the 1998 study was hampered by the lack of adequate system descriptions, despite soliciting descriptions from other panels as early as April 1998. In fact, the bulk of the system descriptions were still unavailable at the end of the first week of the 2-week Irvine meeting. This schedule is not conducive to quality cost-estimating and does not allow any cooperation between the Cost Panel and the other panels to explore more affordable alternatives or cost-as-an-independent-variable analysis between alternate proposals. More fundamentally, it is difficult to even come to the summer meeting prepared with a sufficient set of cost-estimating tools if systems are brought forward in the last week of the meeting. It should be noted that the only major new system receiving a full development recommendation out of the study (the SBR) was the system the Cost Panel had obtained a description of in April.

- The Cost Panel should establish the budgetary baseline at least 1 month prior to the general summer meeting, with coordination of the study director, and provide it and brief it to the other panels no later than the summer meeting kickoff.

  At the start of the 1998 summer meeting in Irvine, the scope of the budget and associated Air Force activities under consideration were still not clear. It was only by coincidence that the majority of the budget had been previously converted to a format suitable for analysis. Nonetheless, considerable effort was expended at the summer meeting, adding additional budget items to this spreadsheet, projecting it to years beyond the PB, aggregating subtotals, and formatting it to match the structure of the options that were chosen for consideration. Much of this effort could and should have been completed prior to the summer meeting, allowing more time to be spent looking at excursions from this baseline. Furthermore, the budget information contained in the baseline would have been invaluable to the Operations Panel if it had been available at the beginning of, or even prior to, the summer meeting. In the future, the Cost Panel should use the POM rather than the PB as the basis of the budget baseline because the documentation describing the content of the POM is more readily available to SAF/AQ[12]. The Cost Panel should consider expanding the scope of the budget baseline in order to provide visibility into some of the costs of other Air Force capabilities, infrastructure, and support that could potentially be included in the trade studies. An example of this might be the cost of airlift saved by use of space assets rather than organic theater assets that would require airlift. Last, qualified personnel and a mechanism to allow the consideration of classified budgets at some level of aggregation might contribute to the thoroughness of the study.

- The industry participants on the Cost Panel should make available sufficient commercial data for the Cost Panel to develop cost trends over time for commercial space systems.

  Much of the methodology used to estimate future systems was based on the premise that market forces will drive down the dollar-per-pound cost of space systems. This methodology is described at

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[12] Assistant Secretary of the Air Force, Acquisition.

length in Section 3.0 of this document. However, we did not collect data that would quantifiably demonstrate this premise. In the past, we have attempted to obtain cost data on commercial space systems, and have been stymied by concerns over the proprietary and competitive nature of the information. There are ways in which trends could be established without any need to release the data supporting those trends. We recommend that, in the future, nondisclosure agreements be put in place to give the Cost Panel access to commercial data that would allow the quantification of trends in commercial space system costs.

- The Architecture and Integration Panel should consider applying intranet technology to facilitate the exchange of data among panels and to enhance the utility of the documentation.

  The SAB study process could be enhanced by the immediate information accessibility and relationships supported by modern intranets. The SAB study had several obvious planes of organization: by panel, by technology or system, by option, and by study product. Furthermore, the relationship of panel results to other panels could be made explicit by hyperlink references. Modern intranets allow documents, models, and other sources and products of information to be organized by direct links between their relevant component information. Search-and-retrieval software can make information resources immediately available to study participants. Implementing an off-the-shelf intranet could significantly enhance both the quality and efficiency of the SAB study process. This would require providing all study participants with 15 minutes of training on how to use a Web browser and conduct searches and providing the technical writers supporting each panel with 3 hours of training on hyperlinking documents and uploading them to a server.

- Within the limits of cost, the Cost Panel requires more computers.

  The Cost Panel was provided with one computer. Fortunately, many panel members brought a laptop or their own personal computer. Competition for the one plain old telephone system wall jack during the study also delayed the reception of critical input from outside sources. For the study to be conducted with the greatest efficiency, each participant needs a computer connected to an intranet.

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Annex 2 to Appendix J

List of Acronyms and Abbreviations

ACEIT	Advanced Cost Estimator Integrated Tool
ACTD	Advanced Concept Technology Demonstration
ADCS	Attitude Determination Control System
AE	Atmospheric Explorer
AF/AQ	Air Force Office of Acquisition
AFB	Air Force Base
AF/XO	Air Force Office of Air and Space Operations
AF/XP	Air Force Office of Plans and Programs
AFRL	Air Force Research Laboratory
AFOSR	Air Force Office of Scientific Research
AGE	Aerospace Ground Equipment
AKM	Apogee Kick Motor
AOV	Aerospace Operations Vehicle
ATD	Advanced Technology Demonstration
C^3	Command, Control, and Communications
CBS	Cost Breakdown Structure
CER	Cost-Estimating Relationship
cm	Centimeter
COMM	Communications Payload
COTS	Commercial Off-the-Shelf
CRAF	Civil Reserve Air Fleet
CRDA	Cooperative Research and Development Agreement
CRSF	Civil Reserve Space Fleet
DARPA	Defense Advanced Research Projects Agency
DMSP	Defense Meteorological Support Program
DoC	Department of Commerce
DoD	Department of Defense
DoT	Department of Transportation
DSCS	Defense Satellite Communications System
DSP	Defense Satellite Program
EELV	Evolved Expendable Launch Vehicle
EMD	Engineering and Manufacturing Development
EOM	End of Mission
EPS	Electric Power System
ESC	Electronic Systems Center
FFP	Firm Fixed Price
FFRDC	Federally Funded Research and Development Center
FLTSAT	Fleet Communications Satellite Program
FMC	Directorate of Financial Management
FOC	Full Operational Capability
FY	Fiscal Year
GBL	Ground-Based Laser
Gbps	Gigabits per Second
GEO	Geostationary Earth Orbit
GMTI	Ground Moving-Target Indication

GPS	Global Positioning System
HSI	Hyperspectral Imagery
IA&T	Integration, Assembly, and Test
ICBM	Intercontinental Ballistic Missile
IOC	Initial Operational Capability
ISR	Intelligence, Surveillance, and Reconnaissance
LCC	Life-Cycle Cost
LTC	Lot Total Cost
MAD	Mean Absolute Deviation
MILPERS	Military Personnel
MILSATCOM	Military Satellite Communications
MIL-STD	Military Standard
MMD	Mean Mission Duration
MPE	Minimum Probable Error
MUPE	Minimum Unbiased Probable Error
NASA	National Aeronautics and Space Administration
NDI	Nondevelopmental Item
NPOESS	National Polar-Orbiting Environmental Satellite System
NRO	National Reconnaissance Office
O&M	Operations and Maintenance
O&S	Operations and Support
OGCs	Other Government Costs
OPR	Office of Primary Responsibility
OSC	Orbital Sciences Corporation
OSD	Office of the Secretary of Defense
PB	President's Budget
PEs	Program Elements
PEM	Program Element Monitor
PME	Prime Mission Equipment
POM	Program Objective Memorandum
R&D	Research and Development
RAC	Rapid Acquisition
RDT&E	Research, Development, Test, and Evaluation
RF	Radio Frequency
SAB	Air Force Scientific Advisory Board
SAF/AQ	Assistant Secretary of the Air Force, Acquisition
SAF/AQS	Assistant Secretary of the Air Force, Acquisition, Space and Nuclear Deterrence
SAF/AQSP	Assistant Secretary of the Air Force, Acquisition, Space and Nuclear Deterrence, Plans and Policy
SAR	Synthetic-Aperture Radar
SBR	Space-Based Radar
SEER	System Evaluation and Estimation of Resources
SE/PM	System Engineering/Program Management
SETA	Specialty Engineering and Technical Assistance
SLOC	Source Line of Code
SMC	Space and Missile Systems Center
SOC	Space Operations Center
SPO	System Program Office
ST&E	System Test and Evaluation
T1	Theoretical First-Unit Production Cost

TDRSS	Telemetry and Data Relay Satellite System
T&E	Test and Evaluation
TOA	Total Obligation Authority
TRI	Tecolote Research, Inc.
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, and Command
UAV	Unmanned Aerial Vehicle
USCM	Unmanned Spacecraft Cost Model
USCM6	SMC’s “Unmanned Spacecraft Cost Model,” Sixth Edition
USCM7	SMC’s “Unmanned Spacecraft Cost Model,” Seventh Edition

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Annex A to Volume 3

Executive Summary

Becoming an Integrated Aerospace Force

The United States Air Force is today an air and space force whose core competencies, as articulated in *Global Engagement*,[1] entail the integrated employment of weapon and support systems across the physical media of air and space. But that force is largely a legacy of the Cold War, it often treats air and space operations as separate activities, and it faces wrenching changes in evolving to deal with the very different world of the 21st century. Among the basic forces that drive decisions from doctrine to system acquisition are:

- Tremendous uncertainty and variability in the situations calling for military action to support national objectives, across the full spectrum of conflict and at any place on the globe
- Continuing withdrawal from forward basing and rapid change to a continental United States–based, globally committed expeditionary force
- A military budget climate characterized by a stringency that has not been seen since before World War II, at a time when significant changes and upgrades in force structure are needed
- Persistent problems with personnel shortages, high operational tempo, aging weapon systems, and archaic information infrastructure, at least some of which are potentially addressable by migrating functions to space
- Levels of growth, diversity, and maturity in commercial space enterprises that consistently outpace the most optimistic forecasts and thereby create an entirely new environment for providing important military capabilities
- The loss of Department of Defense (DoD) and Air Force leverage over commercial space operations, both in determining system capabilities and in being seen as a primary customer
- A long-term trend under which a growing fraction of Air Force resources go to provide services to others rather than to the direct warfighting mission

The future relevance and success of the Air Force—indeed, its ability to remain a preferred instrument of national power in this complex and uncertain emerging world—depend critically on becoming an integrated aerospace force which can execute the responsibilities assigned to it under *Joint Vision 2010* (*JV2010*).[2] The essential capabilities of such a force are concisely expressed as Global Knowledge, Global Reach, and Global Power.

Global Knowledge

JV2010 depends on information dominance to enable virtually every aspect of military superiority. The heart of this capability is a system of systems. It starts with intelligence, surveillance, and reconnaissance (ISR), coupled with real-time communications and information processing. The result, from initial

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[1] *Global Engagement: A Vision for the 21st Century Air Force,* Secretary of the Air Force S. Widnall and Chief of Staff of the Air Force Gen R. Fogleman.

[2] *Joint Vision 2010,* Gen John M. Shalikashvili, Chairman of the Joint Chiefs of Staff, 1996.

collection of data to its timely use by warfighters, is victory through knowing more and knowing it sooner than the enemy.

Today's Capability. Intelligence satellites and airborne platforms provide localized and generally discontinuous sensing, often impeded by weather, terrain, and hostile countermeasures. Processing and dissemination of time-sensitive data to warfighters is improving but still falls far short of the true need.

Tomorrow's Promise. The aerospace force can and must deliver precise, global situational awareness to commanders and fighters at all levels, providing the right information at the right place and time, while overcoming countermeasures and denying similar knowledge to the enemy.

Global Reach

The nation requires global presence to influence events and defend American interests, but with much less of the traditional forward basing. The mobility of aerospace forces is the key to rapid response and to the projection of all kinds of military power from U.S. bases to worldwide contingencies.

Today's Capability. Airlifters and tankers allow expeditionary forces to deploy and are engaged every day in missions from humanitarian relief to combat force sustainment. However, lift is limited, deployments take days to weeks, and success often depends on support from countries in the regions of interest—support that cannot be guaranteed in times of crisis.

Tomorrow's Promise. The aerospace force, with the right organization, training, and equipment, could deliver precisely calibrated effects, from taking a picture to dropping a precision munition, anywhere on earth, in less than an hour from the "go" order, with surprise and immunity to most defenses. Larger-scale deployments would be lighter, faster, and more effective, and the need to station forces in foreign theaters would be greatly reduced.

Global Power

America's military forces must be able to prevail in operations anywhere on earth, ranging from disaster relief to hostage rescue to shows of force and, when required, combat.

Today's Capability. Modern fighters and bombers with steadily improving precision targeting and munitions have impressive ability to prosecute targets with economy of force and greatly reduced collateral damage and casualties. However, proliferating air defenses threaten their survivability, and almost any adversary has or can have the ability to use space-based systems, eroding a long-term U.S. advantage.

Tomorrow's Promise. The aerospace force can and must enable the full richness of the "effects-based targeting" concept,[3] using a wide range of lethal and nonlethal means to shape the desired end state of any conflict. At the same time, real space control, including assured access for friendly forces and denial of the same to enemies, can restore the decisive edge in space operations.

The challenge facing the Air Force is summarized in Figure ES-1,[4] which shows the overarching operational and infrastructure tenets of *JV2010*, the Air Force core competencies which address those tenets, and the ultimate vision of Full Spectrum Dominance. A major conclusion of this study is that the Air Force can achieve *genuinely revolutionary capabilities* which make *JV2010* achievable and which offer unprecedented options for achieving national objectives.

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[3] "The Road Less Traveled," briefing by Lt Gen Gamble, 1998.

[4] "The Air Force After Next … Is Now," briefing to the National Defense Review, Brig Gen Wald, 1998.

Figure ES-1. *The Challenge Facing Aerospace Forces in the 21st Century Is to Develop and Apply Core Competencies That Effectively Implement National Military Policy*

A Revolution in Aerospace Power

In this study, the U.S. Air Force Scientific Advisory Board (SAB) examined the future capabilities and uses of aerospace forces and the courses of action available to the Air Force to achieve advances which are essential to its continued effectiveness. Two examples illustrate the great potential of integrated aerospace power. Figure ES-2 sketches a scenario for precision strike of a terrorist enclave or other time-critical target. It is based on a system capable of delivering precision-guided munitions at orbital speeds,

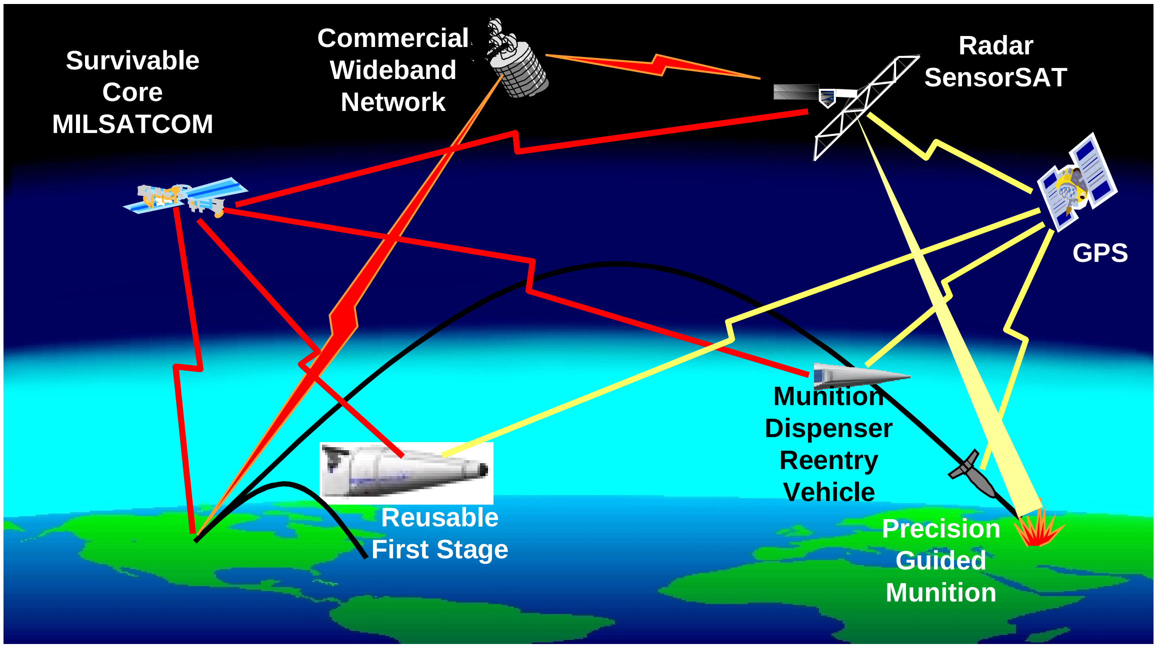

Figure ES-2. *Rapid, Precise, Global Strike Capability Illustrates the Potential of Aerospace Forces to Contribute in New Ways to Achieving National Objectives* combined with global, all-weather, synoptic, high-resolution sensing; precision navigation and timing; and responsive command and control. Such a system would permit destruction of the target in less than an hour from a National Command Authorities order with complete surprise, immunity to currently fielded active defenses, and a lower prospect of collateral damage. It could equally well conduct a photo reconnaissance mission to produce proof that a prohibited action was in progress. At the other end of the spectrum, Figure ES-3 (borrowed from the Information Management study that was done in parallel with this one[5]) suggests the pervasive role of aerospace forces in a major conflict, including the ability to facilitate cooperation of joint and coalition forces to deliver the maximum total military effect. Here, space systems create information-rich warfighters, negate asymmetric threats like theater missiles, and make the diverse elements of the force interoperable. These examples illustrate capabilities that have not been available in earlier conflicts and that have enormous potential to promote the nation’s security and influence.

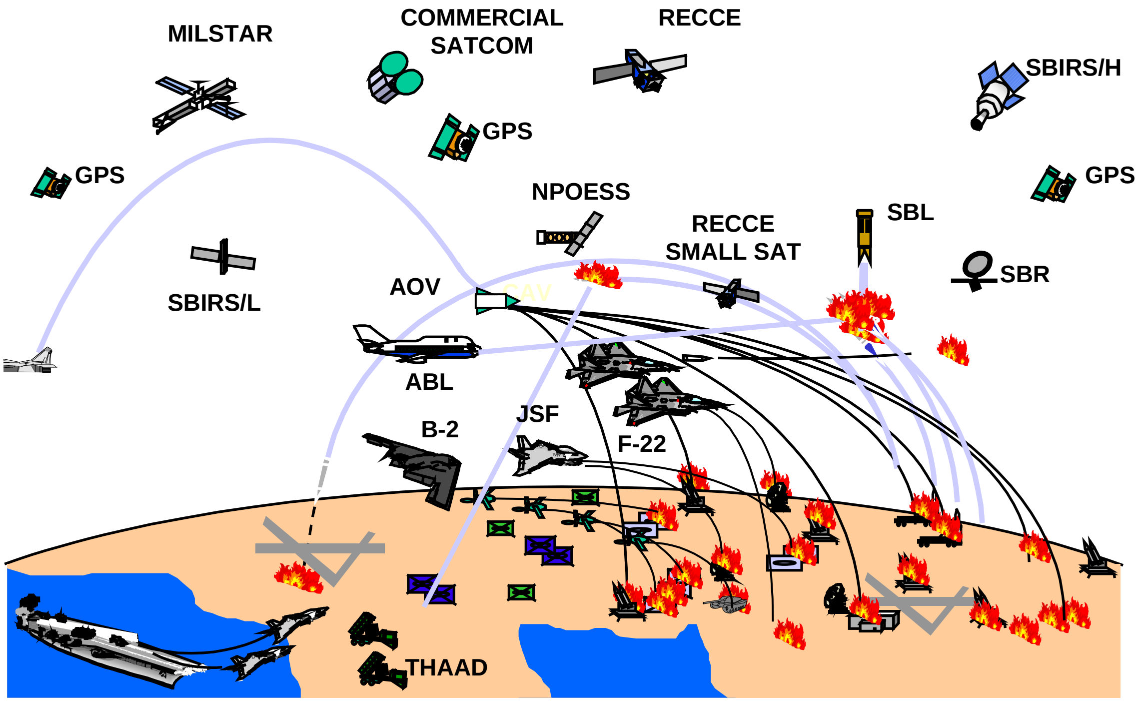

Figure ES-3. *Integrated Aerospace Power Is an Essential Element of Joint and Coalition Warfare*

Paying for Change

However, the other side of this coin is the reality of military budgets and end strengths that are inadequate to satisfy current needs, let alone pay for major new force structure initiatives. In order to fund new and modified systems, the Air Force will have to find ways to save money elsewhere. There are a number of such areas, and all of them involve hard choices. They include

- Getting out of some mission areas, including things like space launch that have a long history as Air Force “stewardship” missions. The Air Force should limit itself to military-unique functions that fall within its core competencies.

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[5] 1998 SAB Study on Information Management.

- Dramatically changing requirements generation, acquisition, and operations to an approach in which buying commercial and applying commercial practices to how the Air Force does business are assumed to be the answer, unless it can be proved otherwise.

- Taking advantage of partnerships, synergism among systems, and carefully scrubbed requirements to pare acquisitions to the minimum that will accomplish the mission. This includes treating airborne and space systems involved in common functions like ISR as an integrated force structure that is optimized as a whole, and thus requires a true system-of-systems architect empowered to enforce such decisions.

- Doing large-scale streamlining of operations, again using commercial models, to eliminate thousands of personnel (whose positions can be used to fill other critical needs) and get rid of expensive and unsupportable facilities and equipment.

- Breaking the mindset that each program area in the Air Force budget has a "fair share" percentage which cannot be changed by other than trivial amounts. Total Obligation Authority (TOA) will probably have to be moved into the space area from other programs, at least in some years of high space activity. Failure to do so will send a clear message to DoD and the world that the Air Force is not serious about taking a leadership role and becoming the aerospace force that the nation needs. However, as discussed in more detail in the body of this report, the available offsets will help a great deal with this problem.

A Vision of the Future Force

In this study, we have started with a vision of 21st century aerospace operations, drawn both from earlier analyses such as New World Vistas and Spacecast 2025 and from the Desired Operational Capabilities and Mission Element Task Lists that describe current Air Force tasking. We have compiled the "baseline" force structure from planning and programming documents (see Table 2-2), and we have evaluated excursions in the form of added or deleted systems and functions. We have assessed the resulting alternatives in terms of four measures of effectiveness:

- Operational Effectiveness—ability of the resulting force structure to address current and projected tasking

- Affordability—ability of the alternative to fit into an executable program within reasonable budget projections

- Technical Risk—availability of the required enabling technologies and products to implement the system or systems under consideration on a given schedule

- Integration—ability of the alternative under consideration to maintain continuity of service to warfighters and to fit into an evolving force structure, including backward compatibility as appropriate

A future aerospace force which can implement this vision, yet be feasible in the likely fiscal circumstances, will be characterized by

- Effectiveness—in executing the exceptionally diverse taskings that will be laid on it

- Survivability—when exposed to new, ambiguous, asymmetric and rapidly changing threats

- Efficiency—in delivering precise effects with great economy of resources

From our analysis, we have arrived at a number of recommendations which are discussed in more detail in this volume and in the individual reports prepared by each of the panels composing the study team. They fall into three categories. Those which impact combat performance tend to support both effectiveness and survivability; those that deal with infrastructure have their primary payoff in improved efficiency. A third set are concerned with how the Air Force does business today and lays the groundwork for future progress. For each recommendation, we suggest one or more Offices of Primary and Collateral Responsibility (OPRs/OCRs) to work the issues, and we give a reference to the section of the main body of this volume where a fuller description is to be found.

We have taken the Doable Space Quick-Look study[6] as a point of departure, and have concentrated on the "equipping" dimension of evolving the aerospace force. Our study complements the work of the Aerospace Integration Task Force (AITF) and other related efforts. We rely on the AITF to develop the conceptual foundation for aerospace employment in the 21st century and to embody it in an Aerospace Integration Plan (AIP). The AIP will define new theory and doctrine for the future aerospace force and the strategies needed for equipping, resourcing, training, educating, and organizing for integrated application of air and space assets. Our results are also fully coordinated with the parallel SAB study on Information Management and support earlier studies on Unmanned Aerial Vehicles and Aerospace Expeditionary Forces. We have enjoyed extensive participation and support from the National Reconnaissance Office (NRO) and have assiduously sought information from the Army, Navy, Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA), and industry. In short, while this is an independent report presenting the objective opinion of the study team, we have worked hard to ensure that all relevant facts, user requirements, joint and coalition warfare concerns, and related programs are properly considered.

Primary Recommendations

Enhanced Effectiveness and Survivability

Move to a Network-Centric, Global Grid Information Architecture. The Air Force should plan and execute the earliest feasible phase-out of noncore military satellite communications (MILSATCOM) operations in favor of commercial services and interoperable user terminals (core MILSATCOM is that capacity which must have levels of assurance and security above what commercial service can provide, presumed to be provided by the Milstar system). Evaluate a maneuverable MILSATCOM system that can be positioned for optimum support to specific theaters as needed. In so doing, the Air Force should maintain backward compatibility to legacy user equipments for a reasonable period of time, but not indefinitely. The Air Force should develop with commercial satellite communications (SATCOM) providers a set of on-orbit gateways to provide robust access for military users. The Air Force should develop and install affordable aircraft SATCOM antennas to provide connectivity between aircraft and the information infrastructure. (See a later recommendation on partnering with industry.) Disparities in military and commercial communications coverage and bandwidth requirements must be resolved before placing primary reliance on commercial services. *Recommended OPR:* HQ USAF/SC. *Recommended OCRs:* SAF/AQ for acquisition, HQ USAF/XO for operational matters, and HQ USAF/XP for long-range planning. *Refer to Volume 1, Section 3.1.*

Develop and Deploy a Global, All-Condition, Intelligence/Surveillance/Reconnaissance Capability. The Air Force should continue current risk-reduction and concept definition efforts, as well as analysis of associated concepts of operations (CONOPS), to define the requirements for a space-based radar system, initially capable of synthetic-aperture radar imaging and ground moving-target indication. The new sensor constellation should complement NRO, civil, and commercial systems in providing the information for global situational awareness, with a target Initial Operational Capability date not later

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[6] Doable Space Quick-Look, AF/ST, 1998.

than 2010. The frequency allocation problem needs continuing attention, preferably in partnership with emerging commercial space radar systems for earth observation. *Recommended OPRs:* SAF/AQ and HQ USAF/XO for current technology and CONOPS developments, respectively. *Recommended OCRs:* SAF/AQ and HQ USAF/XO for overall acquisition and operational matters concerned with each other's OPR responsibilities, and HQ USAF/XP for initial planning and programming for a follow-on engineering development, manufacturing, and deployment program. *Refer to Volume 1, Section 3.2.*

Provide Robust Position, Navigation, and Timing (PNT). In keeping with national policy arising from the recommendations of the Global Positioning System (GPS) Independent Review Team and a proposed Presidential Directive, the Air Force should retain, on behalf of DoD, ownership and management of GPS. The Air Force should provide the advocacy needed to maintain adequate budget priority for purely military PNT functions, especially robust services to warfighters in hostile environments through system improvements and augmentation as recommended by the Joint Program Office. At the same time, the Air Force should continue to provide civil and commercial services, and should vigorously pursue GPS funding from other, especially civil, agencies. The Air Force should similarly develop and field capabilities to selectively deny these services to adversaries. *Recommended OPR:* SAF/AQ. *Recommended OCRs:* HQ USAF/XO for operational matters, and HQ USAF/XP for long-range planning. *Refer to Volume 1, Section 3.3.*

Prepare for Global Energy Projection. Do not proceed with large-scale, on-orbit high-energy laser demonstrations such as the proposed Space-Based Laser Readiness Demonstrator at this time, but pursue aggressively the precursor efforts needed to enable global energy projection at the earliest feasible date. The Air Force should develop a CONOPS for the employment of high-energy laser projection from space, using space-based or terrestrial lasers, and should conduct requirements analysis to identify the most effective and affordable approach to implementing such a system with the capability to deliver tailored effects, both lethal and nonlethal. Alternatives to the usually assumed chemical lasers should be explored, including electrically powered solid-state lasers. No development or deployment decisions should be made until the military worth and optimum approach are established. The Air Force should start now a focused technology development effort in areas supporting high-performance optical systems in space, with emphasis on large, lightweight, low-cost optics. *Recommended OPRs:* SAF/AQ and HQ USAF/XO for current technology and CONOPS developments, respectively. *Recommended OCRs:* SAF/AQ and HQ USAF/XO for overall acquisition and operational matters concerned with each other's OPR responsibilities, and HQ USAF/XP for long-range planning. *Refer to Volume 1, Section 3.4.*

Improve Space Surveillance and Develop a Recognized Space Picture (RSP) Construct for the Common Operating Picture (COP). The Air Force should migrate selected space surveillance functions to space. A possible approach is to modify the Space-Based Infrared System (SBIRS) Low constellation to perform both its primary warning mission and tracking of objects in high orbits.[7] The Air Force should implement enhancements to ground sensors, especially a supportability upgrade to the FPS-85 Spacetrack radar,[8] and should evaluate the value of importing and fusing data from Army missile defense radars. The Air Force should lead the development of an RSP corresponding to existing air, ground, and maritime pictures, under the COP. As a key element of the RSP, the Air Force should provide timely attack warning and reporting for all satellites used by the military. *Recommended OPR:* HQ USAF/XO. *Recommended OCR:* SAF/AQ. *Refer to Volume 1, Section 3.5.*

Protect U.S. Space Assets Against Likely Threats. The Air Force should take a number of steps, including encryption, selective hardening of satellites, use of system and orbital diversity/redundancy, threat location, and physical security for ground sites, to minimize the risk from the most likely future

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[7] *SAB Report on Space Surveillance, Asteroids and Comets, and Space Debris, Vol. 1: Space Surveillance,* SAB-TR-96-04, June 1997, pp. 11-15 and Appendix 1.

[8] Ibid.

threats. The goal should be maximum mission survivability at minimum cost. *Recommended OPRs:* SAF/AQ for acquisition and HQ USAF/XO for operational matters, respectively. *Recommended OCR:* HQ USAF/XP for long-range planning. *Refer to Volume 1, Section 3.6.*

Develop a Space Test Activity and Adequate Modeling, Simulation, and Analysis Tools. It is urgent that the Air Force be better able to demonstrate the military worth of aerospace. The Air Force should ensure that emerging or updated models at the campaign and mission/engagement levels accurately portray the characteristics and effectiveness of air and space systems; one promising opportunity is the National Air and Space Model at the Electronic Systems Center. The resulting analytical capability should be used to support system requirements definition, operational analysis, integration of air and space, and many other purposes. The Air Force should create a space test activity, exploiting existing systems to keep costs low. This activity will be useful for development and operational testing, training, system effectiveness evaluation, and similar purposes analogous to those performed for aircraft by air test ranges, but allowing such activities to occur in the real space environment. *Recommended OPR:* HQ USAF/XO. *Recommended OCRs:* SAF/AQ for acquisition and HQ USAF/XP for long-range planning. *Refer to Volume 1, Section 3.7.*

Preserve the Option to Develop an Aerospace Operations Vehicle (AOV). The Air Force should continue the current Space Maneuvering Vehicle demonstration and perform analysis of associated CONOPS to develop a system concept and a plan and roadmap for a phased program with clear milestones for continued development in the event the results of these activities warrant a follow-on. A program decision should be made in approximately 2002. The Air Force should provide the minimum level of funding in the area of reusable launch vehicles (RLVs) needed to ensure that the NASA-led effort addresses Air Force lift requirements. *Recommended OPR:* SAF/AQ. *Recommended OCRs:* HQ USAF/XO for CONOPS analysis and system concept definition and HQ USAF/XP for long-range planning. *Refer to Volume 1, Section 3.8.*

Space Control. Classified aspects of the Space Control area are discussed in the Space Control Panel report.

Enhanced Efficiency

Transition National Launch Facilities to Civilian Operations With the Air Force as a Tenant. The Air Force should act in two steps to exit the launch operations field except for essential military missions: Step 1—award an omnibus contract for operation of the Eastern and Western Ranges, with economic provisions for modernization of facilities. Step 2—transfer responsibility to a suitable civil agency (e.g., support creation of a National Space Port Authority) for operations and to the Federal Aviation Administration for safety. Continue direct cost commercial launch pricing for onshore launch through the national program. Provide up-front funding, if required, to make privatization feasible as a business opportunity. Phase-out legacy tracking systems in favor of GPS-derived tracking (a “space-based range”). *Recommended OPR:* SAF/AQ for transition policy. *Recommended OCRs:* HQ USAF/XO for operational matters and HQ USAF/SP for long-range planning. Transfer of responsibility involves multiple organizations and national policy. *Refer to Volume 1, Section 3.10.*

Transition Launch to Primary Reliance on Commercial Services. The Air Force should begin an orderly phase-out of most current organic booster procurement and launch programs and should increase use of commercial launch services, leading to primary reliance on them. Retain minimum essential organic launch capability, possibly in the form of the AOV, for payloads that cannot be commercially launched. The Evolved Expendable Launch Vehicle program should be completed, and the Air Force should maintain close coordination with NASA to support RLV technology. Satellite design, especially weight, should be predicated on compatibility with commercial launchers. *Recommended OPR:*

SAF/AQ for transition policy. *Recommended OCR:* HQ USAF/XO for operational analysis and planning. *Refer to Volume 1, Section 3.11.*

Implement Commercial Models and Other Improvements to Satellite Operations and Tracking. The Air Force should streamline satellite operations by transitioning to a commercial model for staffing and system operation; outsourcing noncritical functions; separating payload control from tracking, telemetry, and control to allow optimization in each area; and making selective investments in ground equipment upgrades where justified by manpower savings and other benefits. The Air Force should make better use of Air Force Reserve personnel to raise skill levels and reduce training and turnover in satellite operations. For new systems, developers should be required to apply best commercial practices (e.g., spiral development) and to set and apply performance metrics for human factors. The Air Force should plan and execute an orderly phase-out of legacy tracking assets and replace them with GPS-derived tracking; commercial options for operation and upgrading of tracking systems should be considered. *Recommended OPR:* SAF/AQ. *Recommended OCR:* HQ USAF/XO for manpower and operations planning and reform. *Refer to Volume 1, Section 3.12.*

Enhanced Programs and Practices

Create an Air Staff Concept Development Process and Central Aerospace Architecture Function. The Air Force should create a central focus for dealing with issues associated with (1) an integrated aerospace system-of-systems architecture that balances space, air, and surface capabilities; (2) conducting an ongoing, proactive partnering with the commercial space industry; and (3) aligning the requirements process and acquisition practices with the realities of a space environment that is dominated by commercial enterprises. This includes creation of a concept development process structured around a properly empowered force structure architect and requirements coordinator with the authority to perform trades among force structure segments and coordinate requirements to deliver maximum warfighting capability for the resources available. The aerospace architect is the logical authority to oversee the continuing interaction with industry. No new personnel are required to implement this function, but integration across multiple current Air Staff activities is essential. At the same time, the Air Force should reform the requirements definition process to focus only on key performance/capability parameters and to shorten the requirements approval cycle to be consistent with commercial product lifetimes (which are often 18 months or less). As part of this reform, requirements should be iterated with commercial capabilities to ensure that commercial space is properly accounted for and should replace traditional platform-centric thinking with a capability or mission focus based on employing the best available combination of systems and other assets. *Recommended OPR:* HQ USAF/XP. *Recommended OCRs:* HQ USAF/XO and SAF/AQ. *Refer to Volume 1, Section 5.1.*

Develop and Implement Aerospace Power Doctrine and Strategy. The Air Force should develop the doctrinal basis for integrated aerospace power and should carry it out through strategies that apply that power effectively to satisfy assigned tasks. *Recommended OPR:* HQ USAF/SP. *Recommended OCR:* Air Force Doctrinal Center. *Refer to Volume 1, Section 5.2.*

Improve Acquisition Practices. The Air Force should make both a *revolutionary* change to switch from military to civilian models for system development, procurement, and operations, and an *evolutionary* change based on continuous improvement throughout the program. Elements of this include

- Adopt a policy that the assumed approach to any procurement is to buy commercial, with alternatives such as government system developments requiring justification for an exception to this rule; maintain high-level emphasis to overcome resistance and inertia in the affected organizations.

- Adopt commercial practices such as business case analysis, streamlined procurement, and spiral development of ground segments; develop an acquisition work force with the skills to effectively execute commercial procurements and cooperative endeavors. Use commercial space wisely to exploit its advantages while protecting military interests and meeting military-unique needs.

- Require a comprehensive acquisition strategy as a fundamental part of a program plan from the outset, restore a high-level program review process analogous to the “summits” of prior years, and develop improved cost/performance models that improve visibility into program status and identify effective initiatives to deal with emerging problems.
- Maintain adequate budget reserves in acquisition programs to minimize reprogramming actions and avoid highly visible program disruptions.
- Require human factors practices and metrics in system development.

Recommended OPR: SAF/AQ. *Refer to Volume 1, Sections 5.1, 5.3, and 5.4.*

Focus the Technology Base on Military-Unique Technologies. The Air Force Research Laboratory (AFRL) has initiated action through the FY 00 Program Objective Memorandum to significantly increase support to space and deserves credit for tackling this difficult but necessary reorientation of the Technology Base program. However, both this initiative and the overall health of the Technology Base are in jeopardy as a result of recent budget cuts. In keeping with the overall move to greater reliance on commercial space, AFRL should structure its program on the basis of (a) funding military-unique technology needs not likely to be met by commercial sources, (b) funding competing concepts to those in commercial development, (c) identifying and pursuing opportunities to insert technologies in both commercial and military applications, and (d) maintaining longer-term high-risk/high-payoff technologies where commercial companies cannot justify investing. In addition, AFRL should focus on the areas identified in this study where critical technology needs exist, e.g., for low-cost, lightweight space optics and reusable launch vehicles. Senior Air Force leadership should strongly support AFRL with Office of the Secretary of Defense and the Congress in obtaining approval of the necessary changes. *Recommended OPR:* SAF/AQ. *Recommended OCR:* AFRL/CC. *Refer to Volume 1, Section 5.5.*

Develop and Execute a Coordinated Program for the Integrated Aerospace Force. The Air Force should pursue a coordinated set of programming and budgeting actions to achieve the integrated aerospace force. Building on and continuing the work of the AITF, an executable program should be constructed through TOA adjustments and through economies and transfers of responsibility that help offset resource increases. A preliminary and high-level budget analysis done as part of this study suggests that a large part of the resources required can be made available from within the current baseline space superiority program area, minimizing the requirement to transfer funds from other program areas. A more detailed budget and program analysis is required to quantify costs and economies and develop a coherent programming strategy, including the possibility of transfers of TOA among program areas. *Recommended OPR:* HQ USAF/XP. *Recommended OCRs:* HQ USAF/XO and SAF/AQ. *Refer to Volume 1, Chapters 4 and 6.*

Summary

In order to meet the obligations likely to be laid on it in the years ahead, the Air Force must complete the transition to a flexible, responsive, integrated aerospace force that is organized, trained, and equipped for a broader range of missions and tasks than ever before. In so doing, it must place unprecedented emphasis on affordability and on shedding activities that do not properly belong in the Air Force program. Commercial space and partnerships with other Government agencies offer important opportunities which must be sought out and pursued. Technology breakthroughs increasingly allow us to deploy markedly improved systems while reducing development and operation costs. However, none of this will happen without new approaches and the leadership to put them into action.

Effecting this transition in an era of flat or declining budgets will be brutally hard, and some cherished Air Force traditions and politically powerful vested interests will suffer in the process. The Air Force faces huge budget problems in space (and almost everywhere else) whether this study's recommendations are acted on or not. There is no way out of this dilemma that does not involve both changing fiscal priorities and divesting large pieces of today's Air Force mission and infrastructure. As one example, thousands of military manpower authorizations that are now dedicated to support activities in space system and launch operations can be replaced with a far smaller workforce, largely contracted out, and moved to fill urgent needs elsewhere. This would be consistent with the development of a corps of aerospace warfighters, skilled in all the dimensions of applying spaceborne and airborne instruments of national power.

We are convinced that the Air Force can and must make the necessary changes within the constraints of budgets and system development timelines. Actions should begin immediately to streamline organizations and operations, to make better use of commercial opportunities, and to better incorporate space capabilities into terrestrial operations. For example, procurement of space and airborne ISR systems should be based on an integrated functionality and should account for the contribution of commercial and other Government systems. The result will be to buy fewer platforms and to avoid wasteful overspecification of any single element in the total force structure. The work of the AITF is especially important here.

Inescapably, to reach the levels of capability which we believe will be increasingly necessary, money will have to be spent on several carefully defined new systems and on upgrades to a number of legacy systems. Restructuring of the budget must start during the current Future Years Defense Program (FYDP), and we project significant investment needs to arise toward the end of the FYDP period. These largely can be offset by savings in many areas. Planning and programming preparations should start immediately, along with decisions on organizational restructuring, outsourcing and privatization, transfers of missions and facilities to other agencies, and other economy measures.

We have tried in this study to outline the kinds of actions the Air Force must take and to establish the basis for a concrete and detailed program roadmap which should now be developed through the program planning and budgeting process. We understand the difficulty of the course we advocate. However, the alternative is for the Air Force to become progressively less capable of doing the jobs that will be assigned and less relevant as an instrument of national power. The time to make the commitment and take the first steps is now.

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Annex B to Volume 3

Terms of Reference

BACKGROUND: The growing importance of space systems in the emerging global security environment makes it imperative that the Air Force, as the executive agent for DoD, deploy and operate effective space and transatmospheric systems and associated infrastructure. However, the current costs to develop, manufacture, orbit, and operate space assets in a climate of severely constrained modernization funding limit Air Force options and demand action both to make space systems more affordable and to craft a carefully optimized investment strategy.

Operation Desert Storm has been called the "first space war" in recognition of the role of space systems in providing information to warfighters. This experience highlighted both the potential of space in other than national missions and the importance of making support from space highly responsive to the dynamic needs of customers from the theater commander to the individual combatant. Moreover, the increasing prospect that adversaries will exploit both dedicated military and commercial space systems against the U.S. means that the role of Air Force space forces in providing services to air and surface operations will be complemented by surveillance and control of space itself.

The international world of space is changing dramatically, with strategic partnerships and commercial projects multiplying rapidly. Moreover, the once dominant position of the DoD and NRO in the space arena is moving toward parity by 1998 and is projected to drop to a distinctly minority position, estimated to be less than 25 percent of satellites launched and resources invested, in the near future. The leading example of this trend is a set of American-led commercial communications consortia that will place more than 100 GEO satellites and over 250 LEO satellites in orbit by 2005 with a collective investment estimated at $53B. This profound change in the space community and business will significantly impact the economics of the marketplace, the infrastructure available to all classes of customers, the rules for control of space assets, and the acquisition strategy through which the Air Force obtains required space capabilities. Two examples are the reality of offshore ownership and control of space services which could be used by adversaries and the possibility that proliferation of communications channels may allow a measure of security by burying military message traffic in a much larger volume of civilian transactions.

At the Fall 1996 CORONA, the Air Force senior leadership set in motion a plan for migrating to space a variety of capabilities currently provided by terrestrial systems. These include collection of imagery and signals intelligence, surveillance and reconnaissance sensing, and communications relay. The realization of this vision requires a change in way space systems are developed and operated, including the elaboration of a strategy for optimizing the use of services provided by allies and commercial operators. The cost, time, and risk associated with deploying and replenishing space assets must all come down substantially.

Major operational aspects of the use of space also need improvement, including the integration of space functions into the overall force structure and control of those functions to deliver the right service to the right customer at the right place and time. Space operations must be as routine and reliable as any other military operation. A robust and affordable national defense demands that the unique attributes of space, airbreathing (including UAV) and surface systems be combined synergistically to deliver the full spectrum of operational capabilities.

The investment strategy for going to space must be based on operational needs, fiscal realities, opportunities presented by technology and investments made by others, and time. Operational imperatives such as the need to accomplish intelligence preparation of the battlespace (IPB) in time to support the deployment of a rapid reaction air expeditionary force may best be met by a combination of space systems (response in minutes), UAVs (response in hours) and manned platforms (response in days). The cost to operate and upgrade current airbreathing platforms to maintain required capabilities, which increases as they age, must be balanced against the costs of various replacement options. As systems like AWACS, Rivet Joint, and the U-2 age out of the force, investment funds for migrating their functions to space could become available.

STUDY PRODUCTS: Briefing to SAF/OS & AF/CC in Oct 1998. Report completion by Dec 1998.

STUDY CHARTER: The charter of this study is to:

(1) Analyze the missions in which space or transatmospheric platforms currently or potentially participate, including space surveillance and control and support to terrestrial operations, to determine the roles such platforms can fulfill and to assess the associated system characteristics.

(2) Identify and evaluate options for migrating the capabilities and functions of existing terrestrial (airborne and surface) systems to combinations of space, airborne, and surface platforms. Stress innovation and affordability in the search for alternatives. Assess the availability or enabling technologies and the associated level of risk. Define timelines for implementing various options and group options in near-term (5 years or less to implement), mid-term (5 to 15 years) and far-term (15 years or greater) categories. Apply the best available cost data and cost estimating methods to quantify the cost of each option.

(3) Prioritize the options found to be feasible on the basis of operational effectiveness, affordability, technical feasibility, and time to implement.

(4) Develop a roadmap showing the time-phased investment from science and technology through production, required risk reduction and feasibility demonstrations, actions to achieve operational status, and interactions of investments with funding for existing systems. Include near term decisions and actions needed to begin implementation of the roadmap, recognizing the lead time from investment decisions to on-orbit capabilities.

It is fundamental to the definition and evaluation of future space options that past approaches to the acquisition and operation of military space systems must give way to faster, lower risk, and less expensive ways of delivering support to warfighters. Major themes of the study include the following:

(1) All panels will stress innovation and affordability, seeking new and fundamentally better ways to attain space and air power.

(2) The study will address both the migration of current functions from terrestrial to space platforms and the new and enhanced functions that may become available by operating in space. The focus will be on meeting the needs of warfighters and creating new options for using space and air power to accomplish missions.

(3) The study will stress the ways in which the Air Force can draw upon commercial space, both in terms of business and engineering practices that enhance affordability and responsiveness and in terms of uses of commercial products and services.

Recognizing the limitations on the level and amount of analysis that can be accomplished in a Summer Study, the committee will carry out preliminary analyses and will seek to identify key areas, define measures of effectiveness (MOEs), and frame more detailed analyses for subsequent efforts.

STUDY ORGANIZATION: This Summer Study is part of an overall Air Force investigation of its future in space. A Doable Space Quick-Look study led by the Air Force Chief Scientist will establish important background. The study will draw on all applicable prior work, including SAB studies such as

New World Vistas, UAV Technologies and Combat Operations, and A Vision for 21st Century Command and Control; Spacecast 2020; and, especially, the work of the Quick Look study group.

The study will require extensive interaction with commercial industry and with other agencies involved in space, including NASA, the Army and Navy, the NRO, and Air Force organizations involved in plans, technology development, acquisition, and operations.

The study will be conducted by a committee composed of the study chairman and 7 panels; panel chairs with broad areas of responsibility may designate subpanels as appropriate. The study chairman and panel chairs will constitute an integration committee for drawing together the products of the panels and resolving interpanel issues.

Operational Requirements and Force Integration. This panel will consider the capabilities required for future space and air power operations, from military operations other than war (MOOTW) through major theater warfare (MTW). It will systematically identify and define force options for satisfying these requirements. It will address both space control and support to terrestrial operations, and will evaluate both migration of current capabilities to space, recognizing that this does not necessarily imply placing equivalent systems in space, and the kinds of new capabilities that space platforms afford. It will formulate system concepts for these new capabilities. A specific topic is the migration of ISR functionality to space. The panel will also consider the feasibility and military utility of force applications in space through such systems as a Space-Based Laser and from space to surface targets. It will also establish the interactions among space, transatmospheric, airbreathing, and surface systems in each option and address issues of control, responsiveness, operational tempos, etc. in meeting warfighter needs. The panel will capture the current and projected capabilities and the operating and projected modification costs of existing systems as the point of departure for innovative future options. It will draw on the large existing body of prior analysis of current systems which are candidates for migration to space in such areas as OPTEMPO and response time to contingencies. Since this panel's work provides an essential framework for the other panels, it will provide periodic interim reports to the other panels and will present initial results in the areas listed not later than the SAB Spring Meeting in April 1998.

Payloads. This panel will address sensors, communications, navigation, onboard processing, and other payloads of interest for satellites, transatmospheric vehicles, and airbreathing platforms to satisfy the requirements identified by the Operational Requirements and Force Integration Panel. It will consider issues of platform autonomy, enabling technology and technical risk, use of commercial and existing products and technologies, operational flight software, and system control and integration. The panel will stress ways to reduce cost and weight by exploiting advanced technology and new design principles. It will explicitly consider tradeoffs between complex (multifunction) and simple (few functions) satellites and among various design lifetimes. The panel will seek to identify and use results of prior trade studies in its area of responsibility. It will identify applicable commercial products and services and perform trade studies between these and dedicated military systems in support of prioritization of options.

Space Control. This panel will perform a study parallel to that of the Payloads Panel in the areas of surveillance of space and of weapons and fire control for employment from satellites and transatmospheric vehicles in order to achieve denial, disruption, damage, or destruction of targets. It will consider both directed energy and projectile weapons and will consider tradeoffs among various means of effecting the spectrum of effects from covert denial of service to asset destruction. It will address the use of such weapons to attack both space and terrestrial targets and will consider the implications of such use for both policy and treaty compliance.

Vehicles and Lift. This panel will address launchers and transatmospheric vehicles, with emphasis on major reductions in the cost per unit weight to orbit, major reductions in the time to generate and launch a satellite or transatmospheric vehicle, and use of commercial or other launch services. It will consider both reusable and expendable launchers, with emphasis on the lift needs of Air Force Systems and their differences from other major space flight activities such as the International Space Station and on lessons learned from earlier RLVs such as the Shuttle. It will also investigate satellite buses and associated power, TT&C, thermal management, and other bus subsystems. The panel will emphasize responsiveness, especially time to replenish a constellation after damage or failure and to launch payloads in response to dynamic world conditions and specific contingencies. The panel will evaluate the feasibility of concepts such as preprocurement of standard buses and rapid integration of tailored payloads. It will examine related programs such as NASA's X-33/34 and will address combinations of dedicated military and commercial launch capacity and infrastructure. A major outcome of this panel's work will be to place lift and space vehicle alternatives in a coherent structure that facilitates analysis and comparisons.

Terrestrial Segment. This panel will address ground stations and equipment, human-machine interfaces, personnel and training, interfaces between military space ground environments and other military and civilian systems, and related aspects of the terrestrial segment, recognizing that roughly half the life cycle cost of such systems is currently entailed in this area. It will consider options for reducing the cost of acquiring and operating ground stations, especially the need to move away from system-unique and proprietary ground segments and to lower required staffing and operator skill levels. The panel will address the application of standardization, automation, advanced displays, human factors, and other related technologies and disciplines to reduce the costs of acquiring and operating space systems. It will explicitly consider issues associated with seamless integration of terrestrial segments into overall command and control and combat operations, including ways to achieve needed responsiveness to warfighters at all levels of a force and in joint and combined operations.

Architecture and Information Management. This panel will address the information infrastructure associated with integrated space, airbreathing, and ground systems. It will also consider the technical architecture dimension of integrated force structure and will seek to quantify the required connectivity, asset management schemes, network robustness and fault tolerance, and service times to customers based on operational needs and system concepts. It will evaluate the role of terrestrial communications channels such as undersea fiber optics. It will address security issues, including multi-level security, the impact of inappropriate or inconsistent classification on effective use of space capabilities, and secure connectivity into the battle area. It will explicitly evaluate alternative approaches to providing direct service from platforms to warfighters and the allocation of asset control to combatants, commanders at all levels, and national authorities, working closely with the Operational Requirements and Force Integration panel. It will consider the requirements and constraints posed by joint and combined operations.

Cost Estimation and Acquisition Strategy. This panel will be responsible for developing a cost estimation methodology for the study and for applying that methodology to quantify the costs of the options that are developed. The panel will assemble and, as appropriate, expand upon existing cost models and cost estimating relationships (CERs) and will seek to assemble the most complete data base feasible on the current and projected costs of hardware, software, and services. The panel will seek to establish a basis for valid comparisons among alternatives, e.g., placing a given function on an orbiting or airbreathing platform for a given level of service to customers. The panel will consult both Government and industry organizations in attempting to compile this cost estimation basis. The panel will also address alternative acquisition strategies in light of the rapid evolution of the space community and industry, the paramount importance of affordability, the practical aspects of migration and progressive replacement of terrestrial functionality, acquisition reform, and the need to accelerate the cycle of defining, developing, and fielding space capabilities.

Annex C to Volume 3

Initial Distribution

Headquarters Air Force

SAF/OS	Secretary of the Air Force
AF/CC	Chief of Staff
AF/CV	Vice Chief of Staff
AF/CVA	Assistant Vice Chief of Staff
AF/HO	Historian
AF/ST	Chief Scientist
AF/SC	Communications and Information
AF/SG	Surgeon General
AF/SF	Security Forces
AF/TE	Test and Evaluation

Assistant Secretary of the Air Force

SAF/AQ	Assistant Secretary for Acquisition
SAF/AQ	Military Director, USAF Scientific Advisory Board
SAF/AQI	Information Dominance
SAF/AQL	Special Programs
SAF/AQP	Global Power
SAF/AQQ	Global Reach
SAF/AQR	Science, Technology and Engineering
SAF/AQS	Space and Nuclear Deterrence
SAF/AQX	Management Policy and Program Integration
SAF/SN	Assistant Secretary (Space)
SAF/SX	Deputy Assistant Secretary (Space Plans and Policy)

Deputy Chief of Staff, Air and Space Operations

AF/XO	DCS, Air and Space Operations
AF/XOC	Command and Control
AF/XOI	Intelligence, Surveillance and Reconnaissance
AF/XOJ	Joint Matters
AF/XOO	Operations and Training
AF/XOR	Operational Requirements

Deputy Chief of Staff, Installations and Logistics

AF/IL	DCS, Installations and Logistics
AF/ILX	Plans and Integration

Deputy Chief of Staff, Plans and Programs

AF/XP	DCS, Plans and Programs
AF/XPI	Information and Systems
AF/XPM	Manpower, Organization and Quality
AF/XPP	Programs
AF/XPX	Strategic Planning
AF/XPY	Analysis

Initial Distribution (continued)

Deputy Chief of Staff, Personnel

AF/DP	DCS, Personnel

Office of the Secretary of Defense

USD (A&T)	Under Secretary for Acquisition and Technology
USD (A&T)/DSB	Defense Science Board
DARPA	Defense Advanced Research Projects Agency
DISA	Defense Information Systems Agency
DIA	Defense Intelligence Agency
BMDO	Ballistic Missile Defense Organization

Other Air Force Organizations

AFMC	Air Force Materiel Command
– CC	- Commander, Air Force Materiel Command
– EN	- Directorate of Engineering and Technical Management
– AFRL	- Air Force Research Laboratory
– SMC	- Space and Missile Systems Center
– ESC	- Electronic Systems Center
– ASC	- Aeronautical Systems Center
– HSC	- Human Systems Center
– AFOSR	- Air Force Office of Scientific Research
ACC	Air Combat Command
– CC	- Commander, Air Combat Command
– AC2ISRC	- Aerospace Command and Control & ISR Center
– 366th Wing	- 366th Wing at Mountain Home Air Force Base
AMC	Air Mobility Command
AFSPC	Air Force Space Command
PACAF	Pacific Air Forces
USAFE	U.S. Air Forces in Europe
AETC	Air Education and Training Command
– AU	- Air University
AFOTEC	Air Force Test and Evaluation Center
AFSOC	Air Force Special Operations Command
AIA	Air Intelligence Agency
NAIC	National Air Intelligence Center
USAFA	U.S. Air Force Academy
NGB/CF	National Guard Bureau
AFSAA	Air Force Studies and Analyses Agency

U.S. Army

ASB	Army Science Board

Initial Distribution (continued)

U.S. Navy

NRAC	Naval Research Advisory Committee
Naval Studies Board	

U.S. Marine Corps

DC/S (A)	Deputy Chief of Staff for Aviation

Joint Staff

JCS	Office of the Vice Chairman
J2	Intelligence
J3	Operations
J4	Logistics
J5	Strategic Plans and Policies
J6	Command, Control, Communications & Computer Systems
J7	Operational Plans and Interoperability
J8	Force Structure, Resources and Assessment

Other

USSPACECOM	U.S. Space Command
Study Participants	
Aerospace Corporation	
ANSER	
MITRE	
RAND	

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