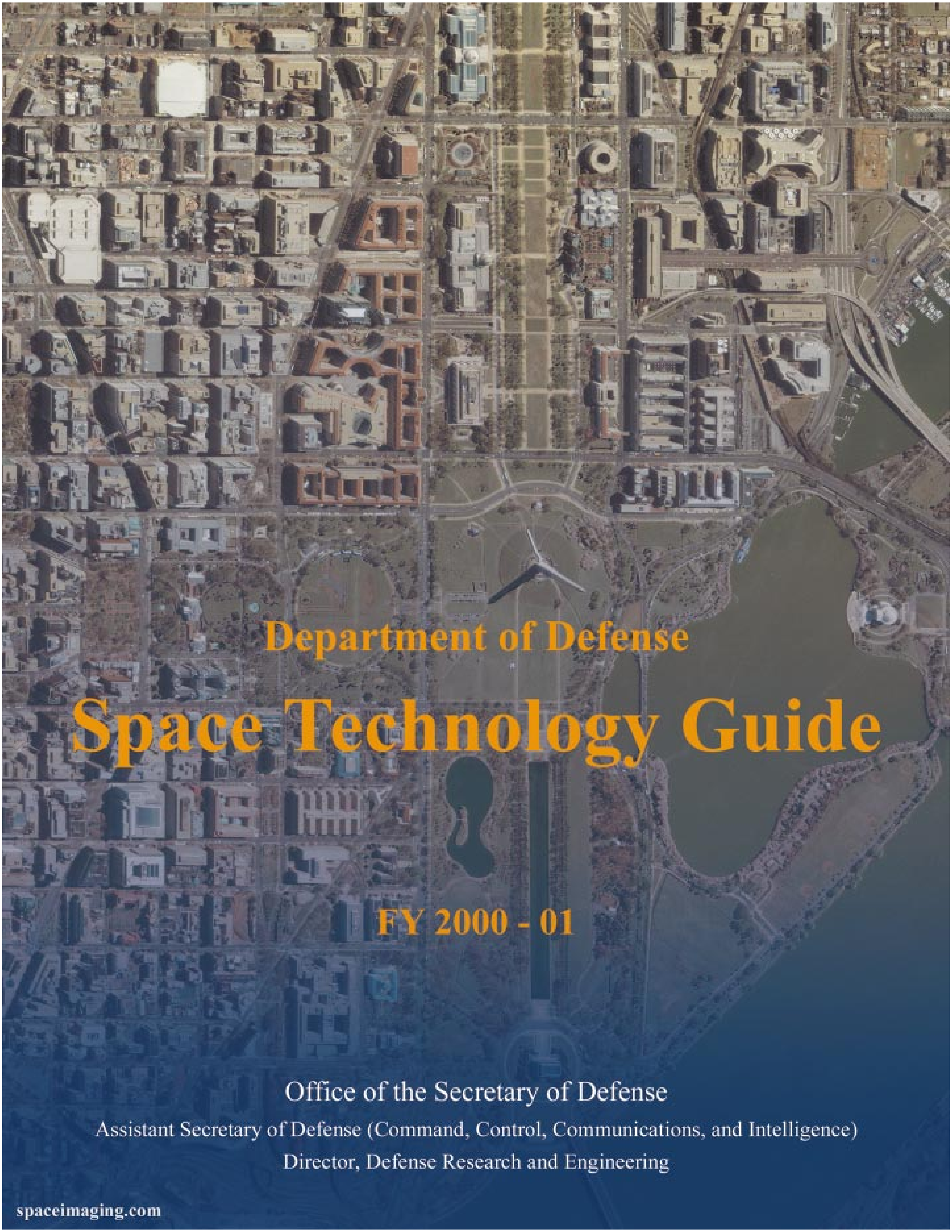

Department of Defense

Space Technology Guide

FY 2000 - 01

Office of the Secretary of Defense
Assistant Secretary of Defense (Command, Control, Communications, and Intelligence)
Director, Defense Research and Engineering

spaceimaging.com

Foreword

Space-based capabilities are integral to the U.S.'s national security operational doctrines and processes. Such capabilities as reliable, real-time high-bandwidth communications can provide an invaluable combat advantage in terms of clarity of command intentions and flexibility in the face of operational changes. Satellite-generated knowledge of enemy dispositions and movements can be and has been exploited by U.S. and allied commanders to achieve decisive victories. Precision navigation and weather data from space permit optimal force disposition, maneuver, decision-making, and responsiveness. At the same time, space systems focused on strategic nuclear assets have enabled the National Command Authorities to act with confidence during times of crisis, secure in their understanding of the strategic force postures.

Access to space and the advantages deriving from operating in space are being affected by technological progress throughout the world. As in other areas of technology, the advantages our military derives from its uses of space are dynamic. Current space capabilities derive from prior decades of technology development and application. Future capabilities will depend on space technology programs of today. Thus, continuing investment in space technologies is needed to maintain the "full spectrum dominance" called for by Joint Vision 2010 *and* 2020, *and to protect freedom of access to space by all law-abiding nations.*

> *If our Armed Forces are to be faster, more lethal, and more precise in 2020 than they are today, we must continue to invest in and develop new military capabilities.*
>
> *Joint Vision 2020*

Trends in the availability and directions of technology clearly suggest that the U.S. pursue its national security space interests vigorously. Dynamics to be addressed by DoD technology investments include:

- *Predictability of our space assets vs. denial and deception techniques employed by opposing forces*
- *The ready availability and military utility of commercial technology for other clients as well as ourselves*
- *Proliferation of ballistic missiles with the risk of nuclear, biological or chemical warheads*
- *The effects of budgetary constraints, which in turn require new concepts and technologies to overcome them*
- *Increasing risks of electronic and cyber attack*
- *The possible need for offensive as well as defensive space operations.*

To counteract these trends, many enhancements and applications of current space technologies are being pursued. The strategy for investing in space technology includes the following approaches:

- Cost reduction – *to be achieved to a significant degree by continuing miniaturization and new paradigms*
- New sensors – *to detect smaller, moving or concealed targets under all environmental conditions*
- On-orbit data processing and artificial intelligence – *to reduce human operator costs and burdens on the communications infrastructure*
- Launcher and propulsion developments – *to reduce costs to orbit and facilitate on-orbit maneuverability*
- On-orbit servicing capabilities – *to extend space system life and upgrade its capabilities*
- Surveillance, defensive and offensive technologies – *to support space control, information operations, and force application.*

These and other operational and technology concepts are summarized in this DoD Space Technology Guide.

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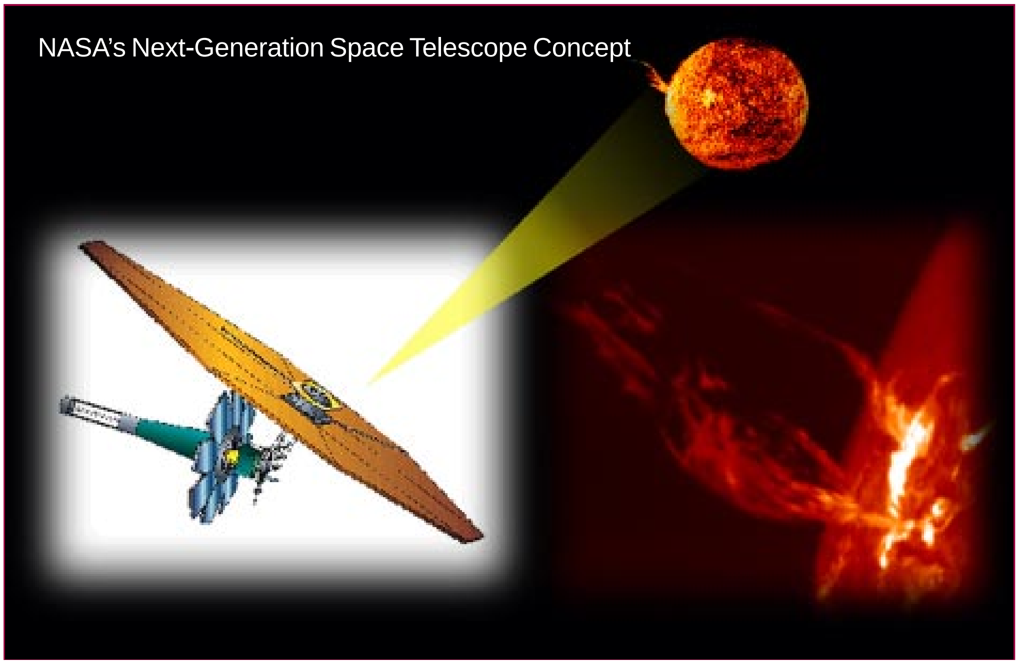

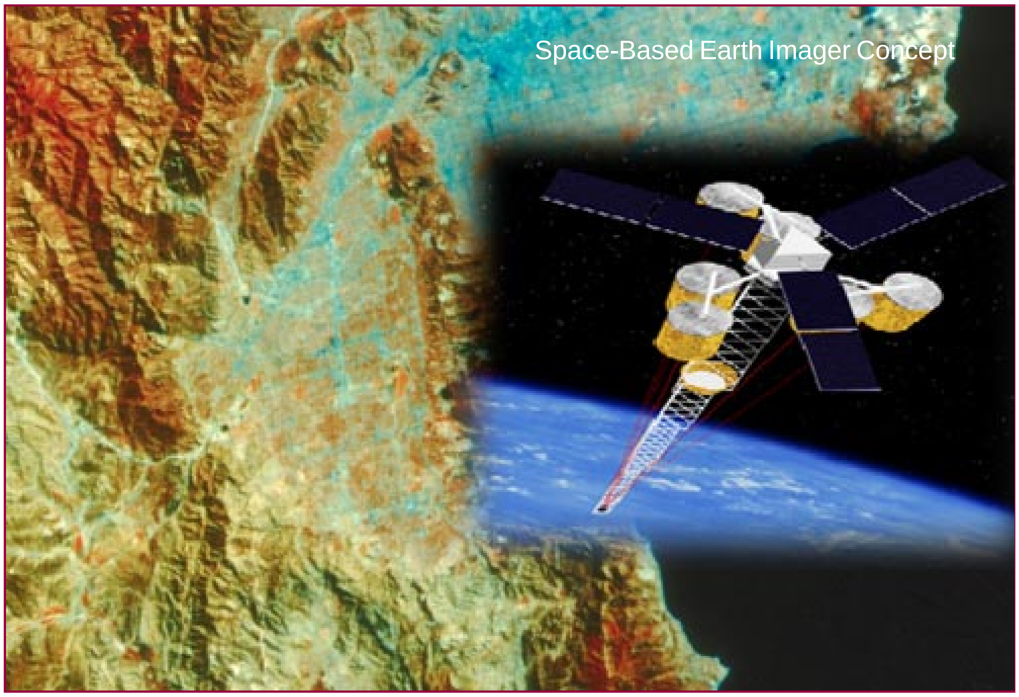

Space-Based Large Deployable Optics Systems

Executive Overview

In its *National Defense Authorization Act for Fiscal Year 2000,*[*] the Congress asked the DoD to:

> . . . develop a detailed guide for investment in space science and technology, and planning and development for space technology systems. . . . [T]he goal shall be to identify the technologies and technology demonstrations needed . . . to take full advantage of use of space for national security purposes.

Approach

In preparing this DoD Space Technology Guide (STG), the full range of national security space-related technology activities needed or under way across the U.S. space community was surveyed. Starting with the U.S. Space Command's *Long Range Plan* of 1998, which implemented *Joint Vision 2010* and provided the basis for Service space planning documents (such as the *Air Force Space Master Plan* of 2000), we reviewed the national security space-relevant portions of the Defense Science and Technology (S&T) documentation, which includes the :

- *Basic Research Plan* (BRP)
- *Defense Technology Area Plan* (DTAP)
- *Joint Warfighting Science and Technology Plan* (JWSTP)
- *Defense Technology Objectives* (DTOs) of the JWSTP and DTAP.

From this research and in conjunction with inputs from the DoD space community, we identified enabling technologies by space missions projected for the future. All of these technologies are in current S&T planning documents and their Defense Department programs or projects are formally described in Research and Development Descriptive Summary exhibits. In turn, these and other documents support the President's Budget and the Future Years Defense Program (FYDP), which are provided to the Congress and in turn subject to the Congressional authorization and appropriation process.

The STG itself addresses the next twenty years, from now through 2020. It projects current and emerging space mission areas that respond to the evolution of current space capabilities to meet national and defense policy guidance and planning, from which space objectives and needs are derived. Thus, each space mission area is supported by relatively unconstrained enabling technologies which, when incorporated and deployed in future systems, will generate capabilities to meet future mission objectives. Many of these technologies support several or (implicitly) even all missions, just as mission evolution continues to merge and expand space missions themselves.

The enabling technologies for microsatellites were independently reviewed and assessed consistent with the Congressional guidance. While addressing a wide range of miniaturization technologies, which are already affecting present missions, the assessment also addressed microsatellite applications, which hold promise of enabling significant new capabilities over the longer term.

Most of the documentation serving as the foundation for the assessment is summarized in the appendices. These include DoD and other Federal agency documentation of their space-relevant S&T projects and the processes by which operational, acquisition and technical communities collaborate to support each other's space-related activities. It is in these sources, representing the overall defense technology base, that the enabling technologies associated with STG space missions are documented. Specific appendices address current space technology demonstrations, the Space Test Program, and a range of private sector activities and space industry views.

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[*] P.L. 106-65–Oct. 5, 1999, 113 Stat. 809, Title XVI, National Security Space Matters; Subtitle A—Space Technology Guide; Reports; Sec. 1601 "Space technology guide."

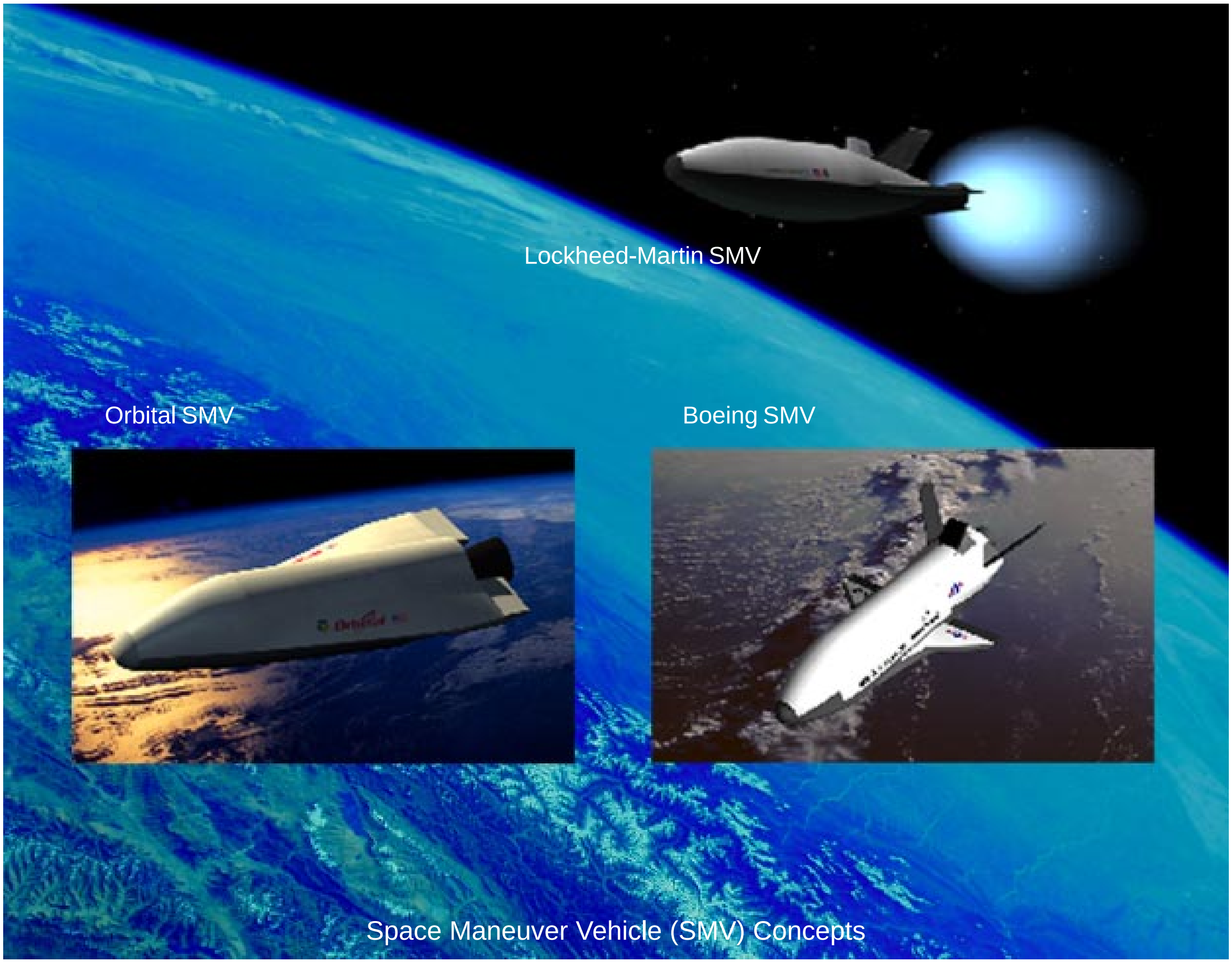
Findings

- There is an extensive number of enabling technologies, covering much of the S&T spectrum, that contribute to the continuing preeminence of U.S. national security space. A few of these technologies are exclusive to space applications, but most comprise the extensive menu from which terrestrial as well as space applications are continually being made. With varying emphasis and often in partnership with other Federal agencies and the private sector, they are the space-relevant technologies in which the Department invests the major part of its research and advanced technology resources.
- Of this large number, a select list represents cross-cutting technologies that not only support multiple mission areas but do so in ways that promise major advances in capability over a relatively short time — to the extent that they represent the possibility of breakthroughs to new levels of capability or system effectiveness, thus amplifing their return on investment. These have been identified as **key enabling technologies**.
- Based in part upon information provided by representatives of the space industry, some technologies are government-unique and some others are not commercially viable. If such technologies are to be developed and applied, then the government must provide the investment. For example, many sensor applications are unique to government requirements and hence are funded solely by the government. Similarly, there are additional technologies that are essential for government missions but which may have or develop commercial application as well; however, the cost of their development is usually so high that industry cannot make a business case for maturing them commercially. Examples include the Global Positioning System, or development of new propulsion concepts.
- The notion of partnerships must be viewed, considered and applied with care. Intra-government partnerships have usually worked well. With the emergence of the Space Technology Alliance; the Air Force Space Command, National Reconnaissance Office and National Aeronautics and Space Administration Partnership Council; and the brokering of partnerships by the Space Test Program, the government has fostered numerous highly productive collaborations that have minimized duplication and leveraged joint resources. Industry/government partnerships have had less success as the latter is driven primarily by national policy considerations while the former is driven by economic market forces. Again, national security space requirements are often unique, while the business case for industry has been risky at best. Typically, the most effective industry-government partnerships have been in areas like launch vehicle propulsion, spacecraft bus and spacecraft propulsion technologies, where companies can readily leverage the joint investment into their commercial market segments and strategic plans. From the DoD perspective these activities have best been fostered by coordinated government/industry-funded programs like the Integrated High Payoff Rocket Propulsion Technology program (IHPRPT).
- The short-term payoffs of the investments in microsatellite technologies will be seen in the application of miniaturization to existing systems to enhance performance and/or capability. For example, smaller lighter components may translate into more fuel for longer life on orbit. Such benefits are immediate and achievable in the near-term. Over the longer term, we expect to see significant microsatellite contributions in special-purpose and “niche” roles, to include enabling new operational capabilities of major significance and cost-effectiveness. For example, a microsatellite or microsat constellation could enhance revisit times and augment imagery during a contingency situation. However, the broad application of microsatellites to the full range of national security missions is unlikely even in the far term. Some limitations imposed by the laws of physics will require larger platforms for the foreseeable future.
- Major space-based technology demonstrations have declined from an average of two or more missions per year to fewer than one per year. Major experiments and demonstrations are typically expensive, even when the launch segment costs are manageable. Military science

payloads get to orbit when other major missions represent the prime payload and bear the bulk of the costs, e.g., via “hitchhiker” rides on the Space Shuttle. Otherwise, experiments must either be tested on the ground (which has significant limitations and risks), be subject to the attrition of budget priorities, or be cancelled when no longer considered priority candidates for limited funding. The Department has now increased S&T funding; however, the lag in space demonstrations will continue over the near term.

The STG’s treatment of the interactions of operational planning and S&T documents and activities yielded the enabling technologies that underlie projected future system capabilities. After analysis of the several space missions’ enabling technologies and both government and industry views of which ones need direct government sponsorship, we identified those whose timely success is critical to our defense space capabilities well into the 21st century. They are the key enabling technologies that “must be done and done right”; i.e., those technologies that may provide major steps forward and thereby leverage other areas to the point where revolutionary advances in space applications and capabilities may ensue.

Consequently, the key enabling technologies listed in the following table represent the results of our review and assessment of the eight mission areas of the STG, where their technologies are specified in greater detail. An illustration of the operational and S&T communities’ interactions with respect to the defense space arena is located on pages 14-5 and -6.



Space Maneuver Vehicle (SMV) Concepts

Key Enabling Technologies

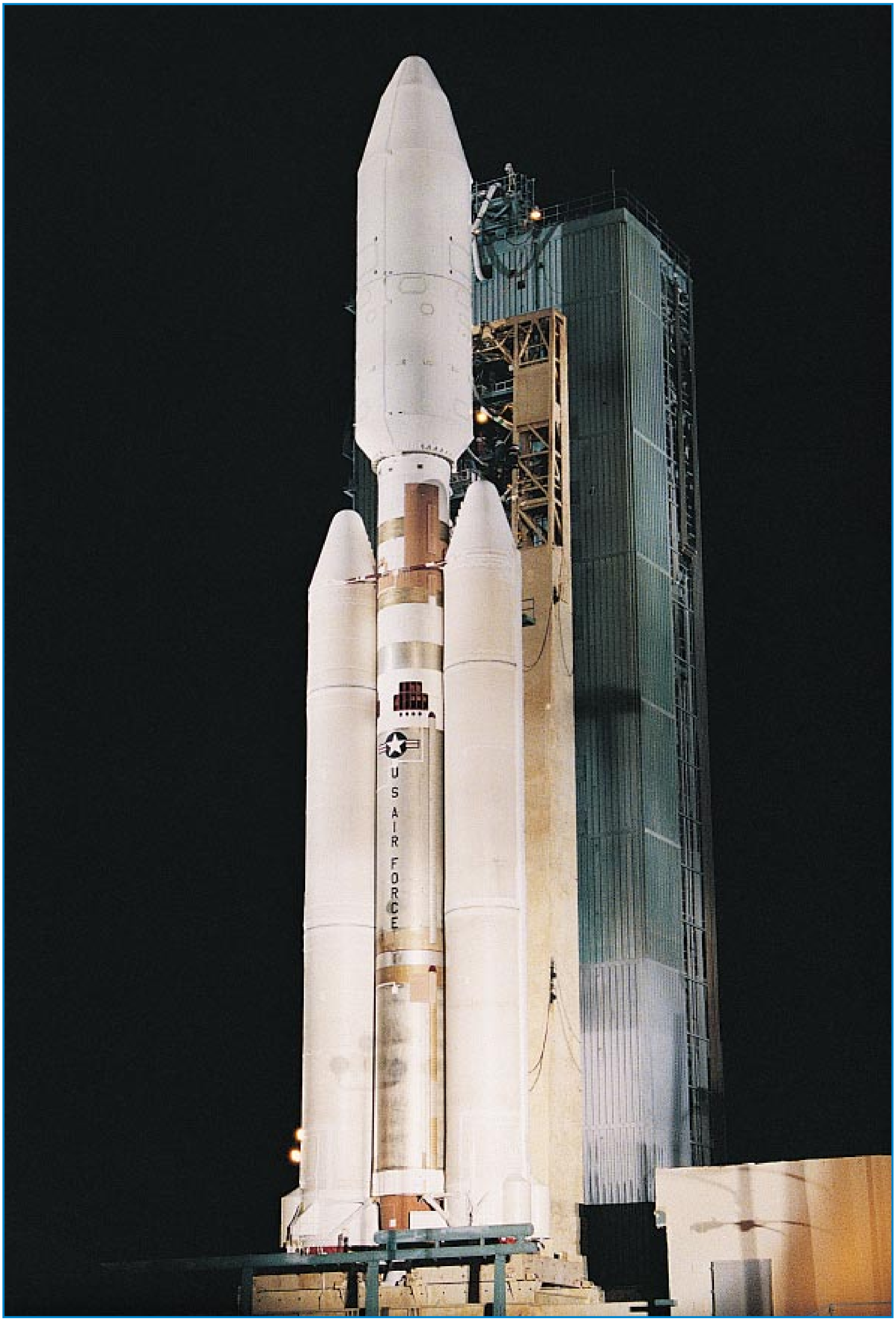
- **Propulsion / Propellants**
  - Advanced cryogenic
  - Full flow cycle
  - Advanced solid rocket motors (SRMs)
  - Combined-cycle (air-breathing engines + rocket)
  - Electric (Hall effect, ion, plasma thrusters)
  - Solar thermal/chemical
  - High-energetic, low-hazard, non-toxic, storable propellants
- **Electric Power**
  (Solar / Chemical / Mechanical;
  i.e., cells/batteries/flywheels)
  - Higher energy density and efficiency
  - Longer life, higher duty cycle
  - Lightweight, thermally stable
- **Structures and Materials**
  - Lightweight, high-strength composites and ceramics
  - Multi-functional, adaptive structures
  - Processing techniques
  - Vibration and thermal control
  - Thin films and environmentally protective coatings and insulation
- **"Thinking" Satellites**
  - Autonomous control
  - Self-assessment/correction
  - Threat detection
  - On-board supercomputing
  - On-orbit robotics
- **More Precise Clocks / Time Sources**
  - Laser/optical, atomic
- **Communications**
  - Lasercom
  - Wideband microwave/millimeter wave
- **Antennas**
  - Large, light, controllable, adaptive space-time
  - Higher frequency
  - Steerable beam phased arrays
  - Higher-efficiency amplifiers
- **Synthetic Aperture Radar (SAR)**
  - Large, light, high-power
  - Interferometric
- **Electro-optic (EO) Sensors**
  - Large, light, deployable, stable, adaptive optics
  - Multi-, hyper- and ultraspectral
  - Large-scale, high-quality focal plane arrays (FPAs)
  - Light, long-life, high-efficiency cryocoolers
  - Uncooled sensing materials
- **Signal Processors (Transmitters / Receivers)**
  - Higher signal-to-noise ratio
  - Higher density devices and circuitry
  - Higher efficiency analog-to-digital (A/D) conversion
  - Advanced encryption technologies
- **Microelectromechanical Systems (MEMS) / Microelectronics / Photonics**
  - Switches and actuators
  - Gyroscopes (e.g. fiber-optic gyros)
  - Inertial measurement units (IMUs)
  - Accelerometers
  - Non-volatile logic and memory
  - Opto-electronics
- **Radiation Hardening**
  - Techniques and components
  - Memory, processors, semiconductor materials
- **Ground Processing**
  - Data fusion
  - Advanced algorithms for processing and exploitation

While these key enabling technologies represent a general focus for Department activity and are deemed prerequisite to far-term space preeminence, they should not be pursued at the expense of the wide range of S&T work that is conducted across the DoD components — much of which has not been specifically identified in this Guide but which also represents important space potential at varying stages of maturity.

The STG itself provides an unconstrained approach via its focus on technology projections well beyond the FYDP, but it is not in a position to address funding and budgetary implications for the next 20 years. While increased funding of many promising areas could accelerate the possibilities for success, specific S&T breakthroughs cannot be guaranteed by money alone. Instead, as a general rule, a balanced and steadily supported S&T program provides the greatest likelihood of success and flexibility in advancing defense space capabilities.

Recommendations

1. Continue to pursue a balanced S&T program to provide the breadth and flexibility to support a wide range of space technology applications to meet current and emerging needs. Within this broad program:
   – Continue to incorporate private sector advances where appropriate in pursuit of this broad S&T program so as to leverage government applications from a broader commercial base.
   – Continue to miniaturize components so as to lower launch costs, extend on-orbit life, upgrade replacement satellite performance, enable new capabilities for satellites of all sizes, and develop new operational paradigms.
   – Sustain investment in advanced technologies to increase reliability, durability, and payload flexibility and reconfigurability.
   – Pursue microsatellite concepts via experiments and demonstrations keyed to proving the component technologies and demonstrating military utility.
2. Focus enough government resources on the key enabling technology areas identified above to assure their timely availability for system and operational applications.
   – Leverage private sector technology investments where possible, but recognize that there are areas where national security applications require unique features and capabilities, and that the government must take the lead in their development.
   – Recognize that, for such cross-cutting technologies to be available when needed, focused but stable investment is required as a prevailing condition.
3. To facilitate technology transition, continue to structure and budget for space experiments and demonstrations as a key part of requisite technology application, maturation and proof of military utility
   – Recognize that experiments and demonstrations represent long-lead, risk-reduction opportunities prior to full-scale development and application, which otherwise could be even more risky and costly.
   – Collaborate where practical via partnerships to share costs and broaden the basis for support.


U S AIR FORCE

1. Introduction

General Approach

The major and increasing roles that space will play in U.S. national security during the 21st century have been documented in other U.S. Government and Department of Defense (DoD) policy and planning documents. These documents describe the needs, i.e., requirements "pull" or "demand," to match the technology "push" or "supply" being provided both by U.S. Government and civil agencies and by commercial interests worldwide.

This DoD Space Technology Guide (STG) surveys the range of national security space-related technology activities needed or under way across the U.S. space community and identifies those whose success is critical to future space capabilities. These are key enabling technologies that "must be done and done right"; i.e., those technologies that may provide major steps forward and thereby leverage other areas to the point where revolutionary advances in space applications and capabilities may ensue. The period of interest is the next twenty years, from now through 2020.

The survey is itself two-fold:

- The STG addresses mission-focused technology areas, derived from space planning and national policy documents. These are discussed in a nondoctrinal way as bases for organizing objectives and concepts that will require new technologies and applications to attain
- Several Appendices summarize DoD and other Federal agency documentation of their space-relevant scientific and technical (S&T) projects and the processes by which operational, acquisition and technical communities collaborate to support each other's space-related activities.

Senior and interagency bodies provide continuing management and oversight to harmonize activities and allocate resources. These functions are an essential planning and programming process that supports program decision-making and S&T investment while keeping requirements achievable and affordable.

This interaction of operational planning and research and development (R&D) documents and activities thus yields the enabling technologies that underlie projected future system capabilities. From this base, the STG identifies those key enabling technologies that promise synergistic results over the long term in meeting national security space needs, and which are thus worthy of DoD investment and sustained support.

Document Focus

PUBLIC LAW 106–65–OCT. 5, 1999   113 STAT. 809

TITLE XVI—NATIONAL SECURITY SPACE MATTERS

Subtitle A—Space Technology Guide; Reports

SEC. 1601. SPACE TECHNOLOGY GUIDE.

(a) REQUIREMENT.—

(b) RELATIONSHIP TO FUTURE-YEARS DEFENSE PROGRAM.—

(c) RELATIONSHIP TO ACTIVITIES OUTSIDE THE DEPARTMENT OF DEFENSE.—

(d) MICRO-SATELLITE TECHNOLOGY DEVELOPMENT PLAN.—

(e) USE OF PREVIOUS STUDIES AND REPORTS.—

(f) REPORT.—

In §1601 of the *National Defense Authorization Act for Fiscal Year 2000*, the Congress asked the DoD to:

> . . . develop a detailed guide for investment in space science and technology, and planning and development for space technology systems. . . . [T]he goal shall be to identify the technologies and technology demonstrations needed . . . to take full advantage of use of space for national security purposes. (see Appendix A)

It further requests "two alternative technology paths," one consistent with Future Years Defense Program (FYDP) funding limitations and the other not subject to funding constraints.

In responding to the Congressional direction, the Department has identified the requisite technologies. All are included in current Defense S&T planning documents, which, in combination with the individual S&T master plans of the Services and Defense Agencies, guide the annual preparation of the DoD budget and Program Objectives Memorandums (POMs). Each activity, however, remains subject to the overall governmental budget process. These technology efforts are also formally described in Research and Development Descriptive Summary (RDDS) exhibits and other documents that support the President's Budget and FYDP, and are in turn subject to the Congressional authorization and appropriation process.

This STG provides an essentially unconstrained approach via its focus on projections well beyond the FYDP, but it is not in a position to address funding and budgetary aspects in explicit terms. While increased funding of many promising areas could accelerate the possibilities for success, specific S&T breakthroughs cannot be guaranteed by money alone. Instead, as a general rule, a balanced and steadily supported S&T program provides the greatest likelihood of success and flexibility in advancing our defense space capabilities.

Defense Science and Technology Program

The mission of the Defense S&T program is to ensure that the warfighters today and tomorrow have superior and affordable technology to support their missions, to include revolutionary capabilities. The development of a strategy to achieve this goal requires understanding of the full range of both military operations and potential threats. The current strategy fosters research that develops new ideas and encourages innovation.

The formal sequence of DoD research and technology development, which underlies the incorporation of new technologies in defense systems acquisition, is organized into three activities:

- **Basic Research:** Budget Activity 1 and Research Category 6.1
- **Applied Research** (formerly Exploratory Development): Budget Activity 2 and Research Category 6.2
- **Advanced Technology Development** (Formerly Advanced Development): Budget Activity 3 and Research Category 6.3A.

The Director, Defense Research and Engineering (DDR&E), is responsible for the overall direction, quality and content of the DoD S&T Program. DDR&E's Deputy Under Secretary of Defense (Science and Technology) (DUSD(S&T)) has established an integrated S&T strategic planning process to discharge these responsibilities, which is pursued and coordinated through the Defense Science and Technology Advisory Group (DSTAG), whose Steering Committee membership is shown below:

DSTAG Steering Committee

- Deputy Under Secretary of Defense (Science and Technology), Chair (DDR&E)
- Deputy Assistant Secretary of the Army (Research and Technology) (Army)
- Chief of Naval Research (Navy)
- Deputy Assistant Secretary of the Air Force (Science, Technology, and Engineering) (Air Force)
- Deputy Director, Defense Advanced Research Project Agency (DARPA)
- Assistant Deputy Director for Technology, Ballistic Missile Defense Organization (BMDO)
- Deputy Director, Defense Threat Reduction Agency (DTRA)

The DSTAG-led Defense S&T Reliance process seeks out opportunities for synergy, integrating the various DoD Component programs into a corporate S&T program, and helps to eliminate unnecessary duplication. Reliance enables the DoD S&T community, working together, to enhance S&T's role in supporting the Department's acquisition programs and their eventual users.

Reliance is responsible for preparing the Defense S&T planning documents:

- The Basic Research Plan (BRP)
- The Defense Technology Area Plan (DTAP)
- The Joint Warfighting Science and Technology Plan (JWSTP)
- The accompanying Defense Technology Objectives (DTO) document.

The three research and technology activities, the DoD's S&T strategic planning process and the S&T planning documents identified above are defined and summarized in Appendices, B, C, D, and E.

The technology applications that have emanated from the multiple interactions of the DoD's and other Federal agencies' broad S&T programs have underlain the military prowess of the U.S. for a century. Our current preeminence in space derives from technologies first researched decades ago. We have seen how the synergistic effects of multiple technologies have yielded revolutionary capabilities for operational systems in the second half of the 20th century. Meanwhile, today's technology projects are yielding the capabilities that will set our course for the 21st century. The DoD's continuing task is to identify and pursue technologies that will continue to preserve our national security.

STG Structure

The STG's following major sections, supported by Appendices, establish the basis for space-related technology analysis. They are:

- Section 2, *Methodology,* which summarizes the approach and techniques employed in identifying, aggregating, analyzing and iterating the technologies associated with the STG missions and other space functions.
- Section 3, *Space Mission Policy and Planning,* which identifies national and top-level documents that provide overall guidance for the STG's focus. These documents and other references are listed in Appendix J.
- Sections 4 through 11 comprise STG-defined defense space mission areas, each of which addresses current and projected space-related operational needs and technologies. In most cases, these mission areas overlap; in some cases, specific functions are common to all. Each of these sections contains the following subsections:
  - **Area Description,** which includes mission focus, capabilities, and implications
  - **Mission Area Objectives,** which lists the mission's key functions, attributes, and projected supporting capabilities
  - **Current Technology Initiatives,** which reflects near-term, FYDP-constrained activity
  - **Enabling Technologies,** which tabulates (on an unconstrained basis) those mission-related technologies that emerged from consolidating operational need statements and S&T activity descriptions
  - **Projected Applications,** which summarizes a more detailed range of near-term experiments, demonstrations and developmental activities
  - **Opportunities for Partnering,** which identifies current or potential interagency collaboration beyond routine administrative processes and coordination.
- Section 12, *Microsatellite Technology,* addresses the effects of miniaturization technologies, both on existing and next-generation "traditional" satellites and upon new, even smaller classes of spacecraft known generically as microsatellites. Near-term microsat experiments and technology demonstrations are summarized as "long-lead" activities to determine technical feasibility and military utility of specific microsat capabilities and new operational concepts.
- Section 13, *Space Technology Demonstrations,* assesses the effects of current funding availability on the broad range of in-space tests and experiments, which are an essential advanced development step to prove both technologies and operational performance prior to commitment to system acquisition. These demonstrations are documented in Appendix G.
- Section 14, *Summary,* provides a short synopsis of findings and recommendations for defense space investment. It identifies the Department's key enabling technologies list, to suggest overall investment attention by the national security space stakeholders of the Federal government and by private industry. Its primary point is that sustained and stable investment in space-related S&T *now* and in the future is key to achieving the requisite capabilities the U.S. will need to assure continuation of national space preeminence well into the 21st century.

Appendices A through K provide additional support and documentary detail for the space aspects of the DoD's S&T program and for the STG itself. Of most relevance:

- Appendix B, *Research and Technology,* summarizes the DoD's space S&T arena and overall coordination process, defines the S&T program/budget activities, and provides an overview of:
    - Appendix C, which summarizes the space-relevant portions of Program 6.1's *Basic Research Plan* (BRP)
    - Appendix D, which summarizes the space-relevant portions of Program 6.2 and 6.3's *Defense Technology Area Plan* (DTAP)
    - Appendix E, which summarizes the space-relevant portions of the *Joint Warfighting Science and Technology Plan* (JWSTP), a document prepared jointly by the DoD's operational and S&T communities
    - Appendix F, which summarizes U.S. Space Command's *Long Range Plan* (LRP), which in turn has provided guidance for Service space planning documents like the Air Force Space Command's *Strategic Master Plan* (SMP)
- Appendix G, *Space Technology Demonstrations*, lists the major activities designed to validate new technologies, approaches, and operational concepts. This appendix also lists recent and planned launches of exploratory payloads under the Space Test Program (STP)
- Appendix H, *Other Federal Agencies,* summarizes the national security-relevant space activities of:
    - The National Aeronautics and Space Administration (NASA)
    - The Department of Energy (DOE), and its national laboratories: Lawrence Livermore (LLNL), Los Alamos (LANL), and Sandia (SNL)
- Appendix I, *Private Sector Perspectives,* surveys industry views, presents selected commercial/industrial space initiatives, and highlights an example of cooperative activity: the projects launched into space in January, 2000, as a government-private sector collaboration under the Joint Air Force Academy/Weber State Satellite (JAWSAT) program.

Key STG Features

The focus of this Guide is on areas for technology investment. It does not seek to prioritize space missions or systems. Similarly, it does not attempt to rank-order the many S&T activities and programs under way or planned by the various DoD component agencies and laboratories.

Instead, the STG addresses technologies more as "commodities" — as S&T activities whose maturation could enhance many missions and systems. Many technologies may have their first effective use in terrestrial environments before they are applied to space; alternatively, initial space applications may be extended to terrestrial arenas. Accordingly, as space capabilities evolve, both technologies and missions will expand their applications and scope.

An additional, but equally important factor is the degree to which technologies reflect defense space capabilities unique to military needs, or for which commercial markets offer no equivalent.

Those that promise major new levels of space mission capability or synergistic applications across space missions — and for which little or no commercial market is available — constitute the Department's key space-related enabling technologies list. They are accompanied by the implicit recommendation for well-planned, stable funding until they either succeed or evolve into new, as yet unforeseen, technology approaches to improved national security capabilities in space.

Key enabling S&T advances through the years, as a basis for U.S. space capabilities in the Year 2000

Photography	1840	Television	1950
Thermoelectricity	1880	Transistor	1950
Cryogenic cooling	1880	Rare earth magnet	1950
Synthetic crystal growth	1880	Maser	1950
Materials equilibrium phase diagram	1880	Atomic clock	1950
Vacuum Tube	1905	Solid-state electronics and integrated circuit	1955
Radio	1905	Solar cell	1955
Photoelectricity	1910	Man-made earth-orbiting satellite	1960
Airplane	1910	Laser	1960
Inertial gyroscope	1920	Kalman filtering (An efficient mathematical estimating algorithm)	1960
Guided Rocket	1930	Fiber optics	1965
Radar	1935	High-temperature superconducting materials	1970
Digital computer	1945	Photonics	1980
Electrophotography	1950		

What is significant in the above list is how long ago many of today's key technologies were first demonstrated, how long it took many of them to mature, and the fact that ***all*** are still being improved through this very day.

Agencies and Organizations Involved in Significant National Security Space Technology Activities

ACDA	Arms Control and Disarmament Agency	LANL	Los Alamos National Laboratory
AFA	Air Force Academy	LLNL	Lawrence Livermore National Laboratory
AFRL	Air Force Research Laboratory	MIT	Massachusetts Institute of Technology
AFSBL	Air Force Space Battle Lab	NASA	National Aeronautics and Space Administration
AFSPC	Air Force Space Command	NAVSPACE	Naval Space Command
ARL	Army Research Laboratory	NIMA	National Imagery and Mapping Agency
ARSPACE	Army Space Command	NIST	National Institute of Standards and Technology
BMDO	Ballistic Missile Defense Organization	NOAA	National Oceanic and Atmospheric Administration
DARPA	Defense Advanced Research Projects Agency	NRL	Naval Research Laboratory
DCI	Director of Central Intelligence	NRO	National Reconnaissance Office
DOA	Department of Agriculture	NSF	National Science Foundation
DOC	Department of Commerce	NSSA	National Security Space Architect
DoD	Department of Defense	ONR	Office of Naval Research
DOE	Department of Energy	OSD	Office of the Secretary of Defense
DOI	Department of the Interior	SNL	Sandia National Laboratory
DOS	Department of State	USA	U.S. Army
DOT	Department of Transportation	USAF	U.S. Air Force
DTRA	Defense Threat Reduction Agency	USIA	U.S. Information Agency
FAA	Federal Aviation Administration	USN	U.S. Navy
FCC	Federal Communications Commission	USSPACECOM	U.S. Space Command
JCS	Joint Chiefs of Staff		
JPL	Jet Propulsion Laboratory		

2. Methodology

Analytic Approach

The purpose of the DoD's Space Technology Guide is two-fold:

- To research and identify enabling technologies that will support emerging defense space systems and missions during the next 20 years and beyond
- To identify those key enabling technologies that the DoD "must do, and do right" for defense space capabilities to evolve in order to meet national security objectives.

The methodology to identify these technologies comprised four iterated processes:

1. Collection by space mission area
   - Multiple sources provided, or were researched for, technologies with defense utility.
2. Association across space mission areas
   - Once collected via mission focus, technologies were evaluated for relative value to other space missions (and common terminology adopted, where appropriate).
3. Assessment by sponsorship/support
   - I.e., whether government or commercial sources could best assure the timely development of needed technologies.
4. Identification of the key enabling technologies that will have the most influential effects on the development of required defense space capabilities
   - I.e., determine those technologies that, among the full range of S&T and developmental activities and projects, need timely DoD investment and sponsorship to benefit our future defense space operations.

Iteration of steps 1 and 2 resulted in the technologies listed in the Enabling Technologies sections of each mission area. A consolidation of those technologies was then:

- Compared with industry views as to proper sponsorship (see Appendix I), and then
- Distilled for those cross-cutting technologies that would both contribute key capabilities and enhance other technologies and capabilities deemed essential for future national security space.

Technology Collection and Sorting

Comprehensive lists of defense space-relevant technologies were initially collected by identifying their role with respect to a space system "work breakdown structure" (WBS). The WBS included the facilities, hardware and software functions that constitute a generic space system, from launch support to on-orbit performance.

Launch	**Control**	**Spacecraft**	
		Bus	**Payload**
(Facilities and Space Launch Systems)	(Ground Facilities and Mission Support Functions)	(Spacecraft/Subsystems Supporting the Payload)	(Mission-Specific Subsystems/Components)

Technologies were then identified with their space missions and defined in greater depth and specificity from both documentary references and subject matter experts. They were iterated several times to determine which mission(s) they supported and to what general level of importance in each case. During this process, their functional order and terminology were standardized to the degree deemed useful in light of their relationships to the missions and to each other. In some cases, where technologies were projected to be mature and applied to well-established missions, they were incorporated in emerging missions in summary fashion to place the emphasis on those technologies more central to performance of that mission.

The goal of such ordering and cross-referencing was to characterize the essential nature of each technology, determine its general space mission/system utility, and thereby provide capabilities to meet needs as they evolve over the next 20 years. This extended approach sought to identify as many missions as a given technology (its applications tailored as appropriate) could support, and whether its role would be relatively major or minor in contributing to the mission's defining needs or capabilities.

<table>
<tr><th colspan="8">Enabling Technologies by Space Mission</th></tr>
<tr><td>Space Transport'n</td><td>Satellite Operations</td><td>C3</td><td>Psn'g, Nav & Timing</td><td>ISR</td><td>Environm'tal Monitoring</td><td>Space Control</td><td>Force Applications</td></tr>
<tr><td colspan="8"><—————————— Technologies supporting multiple missions ——————————>
Roles: MAJOR <– > Minor <–> Little/None</td></tr>
</table>

This approach provided mission-related lists of technologies whose interactive contributions will enable both current and emerging space missions. It should be noted that:

- No mission's technology list is exhaustive; many technological factors are assumed for, or subsumed in, each listing
- The number of missions affected by each technology, while significant, is not necessarily the measure of that technology's importance as a key enabler for future capabilities

However, those listed are the technologies whose successful applications best characterize operational performance in the attainment of mission objectives.

Governmental Role

The assessment process also involved defining technologies according to the most likely role of government as their sponsor/user: DoD-unique (for military use only), DoD as lead (where the military would be the first or major user), or private sector as lead (where commercial uses would predominate). These categories are characterized below.

Technology Characterization		Funding Implication
DoD-unique	• Special defense requirements or characteristics	– Must be funded by government (indefinitely)
DoD as lead	• Significant investment needed and no near-term commercial market projected (i.e., no "good business case" currently exists)	– Government must fund in whole or major part, especially for high-risk technologies (at least until commercial demand emerges)
Private Sector as lead	• A commercial market already exists and is actively developing the technology	– Government can leverage or tailor commercial products to meet national security needs

Industry recommendations for increased government funding focused on launch and in-space propulsion techniques and technologies, radiation-hardening of electronics, and general data processing and exploitation (see Appendix I). Government-funded technologies, whether permanently or initially, in whole or in part, constitute those that are pursued in Federal laboratories or under contract with the private sector.

Key Enabling Technologies

The next step was to select those critical technologies that were needed to sustain or provide major capabilities for the foreseeable future. This list was developed by combining assessments of mission utility and governmental role (i.e., DoD-unique or -lead), and extrapolating them for implications over the long term (through 2020). This Key Enabling Technologies list is presented in Section 14, *Summary.*

Findings and Recommendations

The final steps in the analytic process were to collect observations and findings (some of which accompany the sections to which they directly apply) and to derive recommendations therefrom. They too are presented in Section 14.

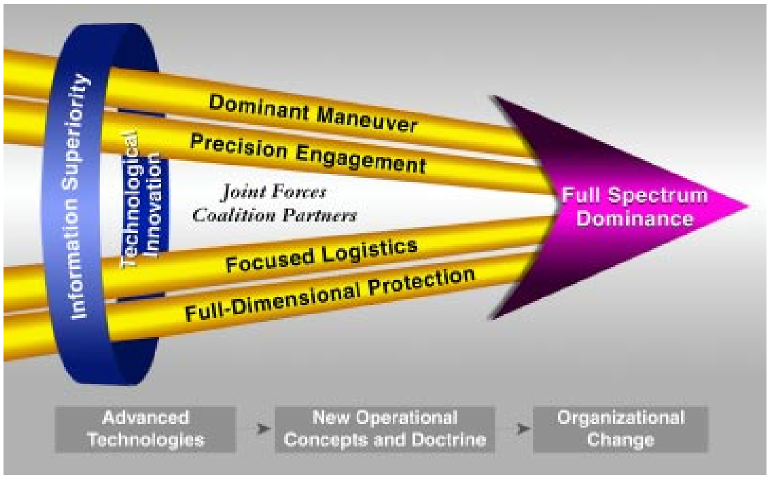
3. Space Mission Policy and Planning

Space Policy and Guidance Documents

In addition to the Defense S&T Planning documents (primarily the BRP, DTAP, and JWSTP), the following high-level documents informed this DoD STG:

- ***DoD Space Policy:*** This 1999 update of the 1987 version incorporated new policies and guidance, to include the President's *National Space Policy* of 1996. It is implemented in the DoD Directive 3100.10, *Space Policy*, to address the themes shown opposite.

- ***Joint Vision 2020:*** With its retention of *Joint Vision 2010's* themes of dominant maneuver, precision engagement, focused logistics and full dimensional protection – all enabling full spectrum dominance – this joint guidance document increases the emphasis on information superiority and innovation, including jointness, interoperability and information operations, to meet asymmetric threats and operate across the full spectrum of military operations.



- **U.S. Space Command's *Long Range Plan:*** USSPACECOM's vision for 2020 provides goals and standards for USSPACECOM and its Service components. It considers technological advances for space capabilities to be key to the U.S.'s future strategic environment. Its four concepts and their key objectives are:

CONCEPT	KEY OBJECTIVES
Control of Space	• **Assured Access** • **Surveillance of Space** • **Protection** • **Prevention** • **Negation**
Global Engagement	• **Integrated Focused Surveillance** • **Missile Defense** • **Force Application**
Full Force Integration	• Policy and Doctrine • People, Information • Organization
Global Partnerships	• Share support for common space services among allied space-faring nations

The operational aspects of USSPACECOM's vision for 2020 are contained in the first two operational concepts above: Control of Space and Global Engagement. In turn, these concepts yield eight "key objectives," which encompass the most challenging of the command's evolving space missions and the capabilities needed to perform them. The systems path and enabling technologies needed to achieve these eight objectives are detailed in Appendix F.

- ***National Security Space Master Plan:*** This living documentation, developed by the National Security Space Architect (NSSA) in conjunction with all space community stakeholders, captures the processes and roadmaps to achieve mid- and long-term architectures across the full range of national security space missions. Among its long-range planning objectives or "guidestars," is Technical Superiority to *"Ensure U.S. leadership through revolutionary technological approaches in critical areas."*
- ***Joint Intelligence Guidance:*** This guidance for U.S. Intelligence programs is developed through a joint process between the Director of Central Intelligence (DCI) and the Deputy Secretary of Defense. Its role includes programmatic influence upon the technologies needed for intelligence activities that support National Security Space.

Space Mission Areas

The following space mission areas are defined to combine both operational focus and technological enablements for future space activity:

Mission Area	Scope
• **Space Transportation**	– Launch and delivery of payloads to orbit and on-orbit maneuver thereafter
• **Satellite Operations**	– Control of launch and early orbital operations, and on-orbit spacecraft telemetry, tracking and commanding (TT&C) functions
• **Positioning, Navigation, and Timing (PNT)**	– Continuous three-dimensional positioning data and a precision timing source for users worldwide
• **Command, Control and Communications (C3)**	– Connection and management of all other operational and support missions
• **Intelligence, Surveillance, and Reconnaissance (ISR)**	– Collection of data from subsurface to space environments, and processing it into information for timely use by a wide range of users and population of national security databases
• **Environmental Monitoring**	– Observation, knowledge and prediction of the terrestrial and space environment
• **Space Control**	– Freedom and security of space operations, plus ability to deny its use to others
• **Force Application**	– Support from space for defensive or offensive military operations

These areas are discussed in Sections 4 through 11, following.

DOE Multispectral Thermal Imager (MTI) image of Albuquerque, NM.

4. Space Transportation

Area Description

Space Transportation encompasses space launch and orbit transfer vehicles and related propulsion systems for the traditional spacelift missions of delivering payloads to orbit and on-orbit spacecraft propulsion for station-keeping, plus emerging missions such as on-orbit refueling, servicing, maintenance, repositioning, and recovery.

The DoD employs both military and commercial expendable launch vehicles, occasionally augmented by use of NASA's Space Shuttle. Military launch systems currently comprise an array of medium- and heavy-lift expendable boosters. The Air Force, NASA and industry are collaboratively funding reusable propulsion technologies with Air Force funding being directed toward supporting militarily unique capabilities. Both independently and in partnership with NASA, industry is developing reusable boosters to add to the launch system inventory and to lower costs to orbit. In addition to military launches, there could be as many as 500 commercial launches worldwide over the next 10 years if costs and risks can be significantly reduced. The DoD is seeking to ease present bottlenecks in access to space via:

- Increased privatization of the launch infrastructure to broaden the launch base
- A launch-on-demand capability, especially for Space Control and other missions where timeliness to orbit or reconstitution of high-demand space-based systems may be paramount.

This area represents the *sine qua non* of space power: unless sufficient lift capability becomes readily available at significantly less cost, U.S. capabilities to place its projected systems on orbit in sufficient quantities to achieve mission objectives will increasingly lag behind demand. Major technological advances leading to improved launch capability will be needed to achieve the very first of USSPACECOM's objectives for the future — Assured Access to Space — without which its other objectives may remain beyond reach.


Propulsion Technology

Improvements to lift capability may be achieved by improving launch and propulsion systems, by reducing the size and weight of spacecraft and payloads, or by some combination of the two. Heavy lift will be needed indefinitely for outsize cargo, so improvements in engines and propellants continue to be a priority. On the other hand, as increasingly fewer spacecraft can do more from a given orbit and/or live longer on orbit, replacements are needed less often, which also reduces relative demand on launch assets. The advent of reusable launch vehicles (RLVs) will reduce per unit launch costs even further. In parallel, we continue to reduce spacecraft size and weight on both a unit and constellation basis. As this miniaturization approach enables entire new classes of small and microsatellites to meet mission utility criteria (see Section 12), the space transportation infrastructure of the future may also include assets that remain on orbit or are recoverable for reuse. Such space support vehicles could provide orbit-changing and maintenance services, thus potentially reducing the life-cycle costs of many space systems.

Several system approaches are summarized in "Projected Applications" below, ranging from current acquisition programs to far-term concepts dependent on near-term technology investment and successful results. In addition, commercial initiatives may also be leveraged for national security space utility (see Appendix I).

When these trends and tradeoffs are additionally augmented by on-orbit servicing and replenishment functions (see Section 5), projected launch assets and on-orbit transfer techniques will achieve new levels of capability, efficiency, and flexibility. As a far-term objective, our national space capabilities would be enhanced immeasurably if space launch, on-orbit maneuvers and even recovery could become as responsive, flexible and reliable as they currently are for manned aircraft.

Mission Area Objectives

- Access to space to be:
  - Routine
  - Assured
  - Low cost
  - Low risk

  with:
  - Launch on schedule (LOS)
  - Launch on demand (LOD)
  - Orbit transfer
  - On-orbit repositioning and servicing

Supporting Capabilities

Reusable into-orbit vehicles (space planes, air launch concepts)
Reusable high-performance rocket engines
Air-breathing/rocket engine combinations
Improved guidance and precision control
Alternative fuels and power sources
Reduced spacecraft weight and cost
Standard modular interfaces
Graceful reentry

Current Technology Initiatives *(Highlights of Current FYDP)*

Space Transportation technology initiatives are spread across several areas: vehicle structures, propulsion, power, materials, thermal protection systems, and flight and ground systems.

The largest investment is in the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. IHPRPT is a jointly planned national initiative which coordinates the efforts and investments of the military Service, NASA and industry to demonstrate aggressive propulsion technologies, whose goals include:

- Significantly reduced launch costs
- Increased satellite life and on-orbit capability (repositioning and potentially on-orbit servicing or retrieval)
- Increased tactical missile effectiveness
- Sustainment of strategic systems capability.

Advanced materials and component and propulsion system technologies for solid, liquid, hybrid, solar electric, solar thermal and gel propellant systems are being pursued to provide these capabilities.

The boost and upper-stage development will also address technology needed for the Military Spaceplane (MSP) system. The goal of this area is to increase the performance of rocket engine systems while also increasing their operability and lowering cost.

Space propulsion work includes both propulsion technologies and power storage devices. Electric propulsion technologies like the Hall Thruster and the Pulsed Plasma thruster will enable longer on-orbit satellite life through more efficient uses of fuel. Improved batteries for power storage will increase the power to subsystems while also increasing battery life. The proposed Orbital Express program will develop and demonstrate robotic techniques for on-orbit functions that could support a wide range of future national security and commercial space programs.

For thermal protection systems, more weather-tolerant and robust materials are being developed as well as mechanical attachments for rapid removal and reattachment. Numerous flight and ground systems are addressing rapid turnaround and reductions in the support infrastructure for launch vehicles.

Selected project detail is tabulated in “Projected Applications,” below.

Enabling Technologies *(Unconstrained)*

Boost and Orbit Transfer Vehicles and Propulsion:

- Vehicle structures and materials
- Structural controls and dynamics
- Guidance, navigation and control
- Cryogenic liquid oxygen/hydrogen rocket engines (cryoboosters, upper stages)
    - E.g., turbo pumps, combustion chambers, hydrostatic bearings, radiation-cooled nozzles, materials, controls
- Hydrocarbon liquid rocket engines
- Solid rocket motors (SRMs)
    - E.g., composite cases and nozzles, propellants, insulation
- Combined-cycle engines (air-breathing gas turbines and rockets)

Spacecraft Vehicles and Propulsion:

- Multifunctional structures and materials
- Cryogenic cooling
- Guidance, navigation, and control
- Electric propulsion (Hall effect, ion and plasma thrusters)
    - E.g., power-processing electronics, propellant flow controls, magnetics
- Chemical propulsion
- Post-boost control systems
    - E.g., propellants, valve materials, controls
- More efficient solar cells and batteries (chemically or thermally generated electricity, such as thermionic power generation and thermo-electric conversion)
    - E.g., lithium ion/polymer hybrid batteries
    - Affordable solar cell materials and manufacturing

Generic Propulsion (Boost and Orbit):

- Lightweight, high-temperature materials for rocket engines
    - E.g., ceramics, rapidly densified carbon-carbon, nanophase aluminum
- Solar thermal/chemical propulsion
    - E.g., inflatable/expandable concentrators and structures, combustion chambers, propellant management, materials
- Protective coatings, thin films
- Interoperable (plug-and-play) software, electrical and mechanical interfaces
- Guidance, navigation and control technologies
    - E.g., gyroscopes, accelerometers, inertial measurement units (IMUs), and wind look-ahead for dynamic pressure and bending moment reduction
- Propellants
    - E.g., energetic low-cost, low-hazard and nontoxic chemical propellants (with higher specific impulse and long storage capabilities)
- Structures and shielding
    - High strength-to-weight and composite materials, processes, and manufacturing techniques; e.g., non-autoclave processing materials and methods for large tanks
    - Vibration, acoustic and thermal control and protection
    - Radiation hardening and shielding of components
    - Lightweight, radiation-hardened and/or composite materials, and their design and processing
    - Integrated vehicle health monitoring (IVHM)
- Non-destructive evaluation (NDE)

Reentry:

- Advanced temperature/erosion/vibration-tolerant materials and technologies to assure reentry for reusable spacecraft:
    - Advanced materials for SRMs and reentry vehicle leading edges
    - Plasma effects technology to minimize signal blackout
    - Improved window/antenna materials for reentry systems.

Projected Applications

Applications evolve from expendable to largely reusable boosters during the next generation.

Category	Project	Status	Agency
Launch on Schedule **Low-Cost Launch Vehicles** To provide low-cost, routine and reliable access to space	• ***Evolved Expendable Launch Vehicle (EELV)*** to lower launch costs by ≥25% – Medium- and heavy-lift variants (MLV, HLV) – First MLV launch planned for FY02; first HLV launch planned for FY04	Engineering Development	Air Force
	• ***Integrated High Payoff Rocket Propulsion Technology (IHPRPT)*** Joint DoD/NASA/U.S. industry S&T program for space launch, spacecraft, and strategic and tactical missile propulsion development – Solid Booster Demo in FY01 (EELV and air launch concepts) – Hall Effect Thruster: Life testing complete in FY01 – Solar Thermal Integrated System: Ground test in FY01 – Cryo Upper Stage Expander Cycle Engine Demo in FY02 (EELV, Atlas, Delta, Titan) – Cryoboost (full flow cycle) Engine Demo in FY03 (for EELV and Reusable Launch and Space Operations Vehicles) – Post-Boost Control System Demo in FY03 – Aging Surveillance Demo in FY03 – Phase II Liquid Engine Demo in FY05	Technology Development and Demonstration	Air Force Navy Army NASA Industry
Launch on Demand **Military Spaceplane** To combine atmospheric and space transportation technologies	• ***Reusable Launch Vehicle (RLV)*** – Next-generation Space Shuttle – Flight-testing of X-33 subscale prototype to follow FY00 ground tests; tests for X-37 to follow thereafter – Goal: To lower payload-to-space cost by up to 10x (to as little as $1000/lb)	Demonstration (2nd-Generation Development)	NASA
DoD will leverage RLV technologies for its own space lift and transportation concepts	• ***Space Operations Vehicle (SOV)*** – Continental U.S. (CONUS) -based reusable light/medium-lift space transportation vehicle (technologies from NASA's X-33 RLV prototype)	System Concept	Air Force
	• ***Space Maneuver Vehicle (SMV)*** – Reusable spacecraft deployed from the SOV to deliver satellite payloads, perform on-orbit reconnaissance and other functions for up to a year, and return to Earth for service and reuse (X-37; X-40) – X-40B projected as a militarized X-37 (to be used as an operational demonstrator)	System Concept	Air Force
Air Launch Concept	• ***Air Launch Vehicle*** – Reusable aircraft coupled with solid rocket launch system	System Concept	Air Force

Category	Project	Status	Agency
ORBIT TRANSFER **Spacecraft/Orbit Transfer Vehicle** To use advanced propulsion concepts to reposition spacecraft, once on orbit	• ***Advanced propulsion concepts,*** such as: – Electric (ion/Hall/pulsed plasma thrusters) – Solar thermal	Technology Concepts	Air Force
	• ***Orbital Express (OE)*** – Combine new technologies, operational concepts and modular spacecraft design at significantly reduced life-cycle costs (LCC)	Technology Concept (ATD Proposal)	DARPA
ON-ORBIT SERVICING **On-Orbit Servicing Vehicle** For spacecraft diagnostics and repair, and replenishment of its consumables while on orbit	– OE's Autonomous Space Transporter and Robotic Orbiter (ASTRO), its micro-shuttle, will demonstrate capability to host and provide bus services to microsatellites, and would enable the design of new-generation satellites capable of on-orbit refueling and electronics upgrade, thus further reducing launch costs while providing life-extending configuration and operational benefits – OE's next-generation satellite (NextSat), a modular and reconfigurable spacecraft and payload with standardized modules and interfaces, will demonstrate serviceable satellite feasibility, mission utility from on-orbit avionics upgrades, increased design flexibility, and lower costs – OE would also develop technologies for "space delivery vans" to provide orbit-changing services to a variety of spacecraft		

Opportunities for Partnering

Under the national DoD/NASA/U.S. industry IHPRPT program, the Air Force is teamed with NASA, the Army, the Navy and the major U.S. propulsion contractors in joint, goal-oriented planning and development of new technologies. These investments provide the foundation for new space propulsion capabilities and resolution of current propulsion-related problems. The eight major IHPRPT demonstration programs are listed chronologically in the preceding table, and described more fully in Appendix G.

NASA's investment in its Integrated Space Transportation Plan (ISTP) program could provide the DoD with many of the technologies required for the SOV and SMV programs. Industry partnerships will be needed to focus and develop technologies for the Air Force's Spacecraft/Orbit Transfer Vehicle (SOTV) program. Close coordination between DoD and NASA will provide smooth technology transition. DoD's focus will be to share costs with NASA on programs applicable to military systems, with particular emphasis on system operability. The Air Force will leverage the DoD and NASA Dual Use S&T programs to help fund the SOTV and associated technologies in association with industry. NASA has expressed an interest both in flight-testing a larger-scale X-43 with the HyTech-developed scramjet engine and using it in a series of flight demonstrations of a wide variety of potential engine configurations.

The DoD Space Test Program (STP) conducts space missions to provide risk-reducing demonstrations of advanced technologies in operational space environments for DoD agencies that do not have routine access to space. With the Air Force as executive agent, the STP supports spaceflight for the military Services and many other U.S. Government agencies (see Appendix G).

5. Satellite Operations

Area Description

Satellite operations (SatOps) are conducted to:

- Verify and maintain satellite health
- Reconfigure and command the spacecraft
- Detect, identify and resolve anomalies
- Perform launch and early orbit operations.

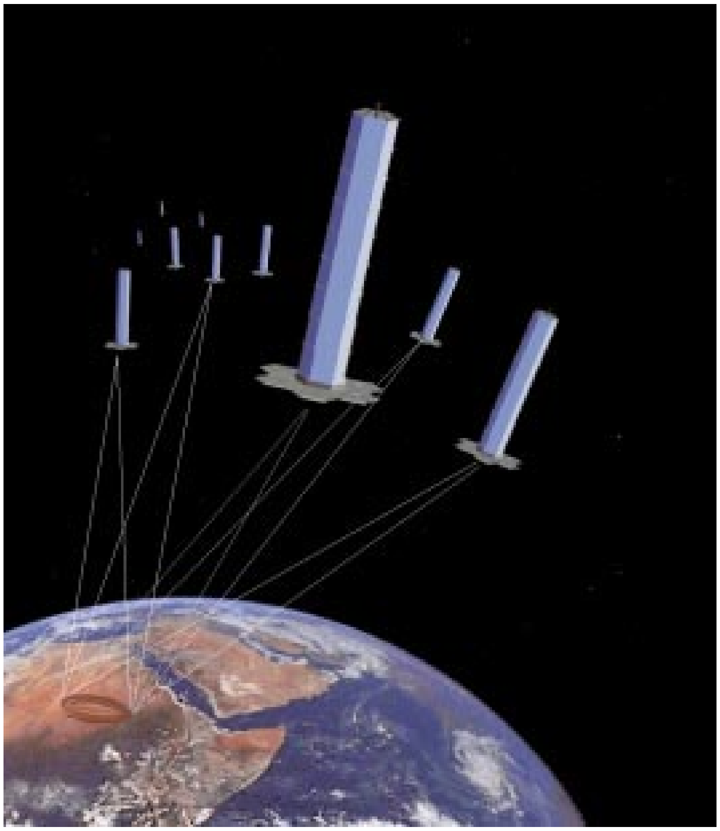
Additionally, any systems required to maintain the spacecraft operations that are not payload-specific are considered in this area.

Traditionally, the three basic functions of SatOps are telemetry monitoring, tracking, and commanding (TT&C). Satellite operational activities and their prior planning are typically labor-intensive.

Emerging space-based architectures will stretch the capacity of current SatOps. This can happen in one of several ways. Increased sensor data collection capability will require high-capacity communications. Individual satellites may be expanded into constellations (i.e., networks of satellites) to provide global coverage, thereby increasing the complexity of operations. Clusters of cooperating and maneuverable satellites may replace single satellites and may enable new missions and performance capabilities, but will also complicate command and control (C2). These new missions may need high-speed data links (ground-to-space and space-to-space), on-board intelligence, and a new ground support infrastructure.

On-orbit refueling and servicing of operational satellites would extend spacecraft life and effectiveness. On-orbit refueling and improvements in propulsion efficiency would enable surveillance constellations to maneuver more, whether for survival, to inspect space objects, or simply to change orbits more readily. On-orbit servicing would involve replacement of components (such as batteries) and insertion of "plug-and-play" modules (such as processors and data storage units). These new concepts would also need a new support infrastructure, such as orbit transfer vehicles and upgradable or reusable spacecraft.

Effective SatOps is the other contributor to Assured Access: once on orbit, space-based capabilities must remain reliably available. Moreover, the more spacecraft that are placed in more orbits, the more complex and important their effective operation becomes. From human ground-based control of individual satellites, future constellations will need to interoperate and perform more of their own housekeeping functions autonomously, with the human role "reduced" to monitoring and emergency responsiveness. Multi-satellite and multi-constellation operations and control would need to become routine so that primary focus may be on their mission-specific products and services for the warfighter and other customers. Both NASA and DARPA, as well as the Services, are pursuing spacecraft autonomy as an enabler for many on-orbit functions. When this capability emerges, questions of when and how humans will need to be in the monitoring and decision loop will also need to be addressed — not only for spacecraft life, health and orbit-keeping, but also for functions ranging from servicing to weapons management.



Distributed Spacecraft

Mission Area Objectives

Enduring		*Secure*	*Robust*	
Integrated operation/mission planning	On-demand command and control	Precision tracking and geolocation of critical space assets	Global space traffic control	Routine on-orbit satellite servicing
Autonomous, fault-tolerant, gracefully degradable SatOps				

Supporting Capabilities

Use of Global Positioning System (GPS) for launch range safety and spacecraft position determination

Space-based relay for telemetry and command dissemination

Improved terrestrial and space weather forecasting for launch and satellite operations

Standard protocols for space-to-space communication links

Advanced command and control networks and architectures

On-board fault detection, isolation, and recovery

Increased fault-tolerance and graceful degradation

Advanced, robust and high-volume on-board processing

Advanced constellation/formation flying concepts and techniques

On-board precision navigation; rendezvous/station-keeping concepts and techniques

On-orbit servicing functions: re-supply of consumables, repair/replacement of components, and reconfiguration of spacecraft

Distributed/collaborative satellite clusters

Interoperable, modular and standard spacecraft components and interfaces

Current Technology Initiatives *(Highlights of Current FYDP)*

Several projects are investigating the use of distributed systems of microsatellites, flying in formation and working together, to perform space missions. Among the challenges of this approach is how to command and control clusters of satellites most efficiently. New techniques are needed to allow an operator to treat a cluster as a single "virtual" satellite, and thus avoid increasing ground operations cost.

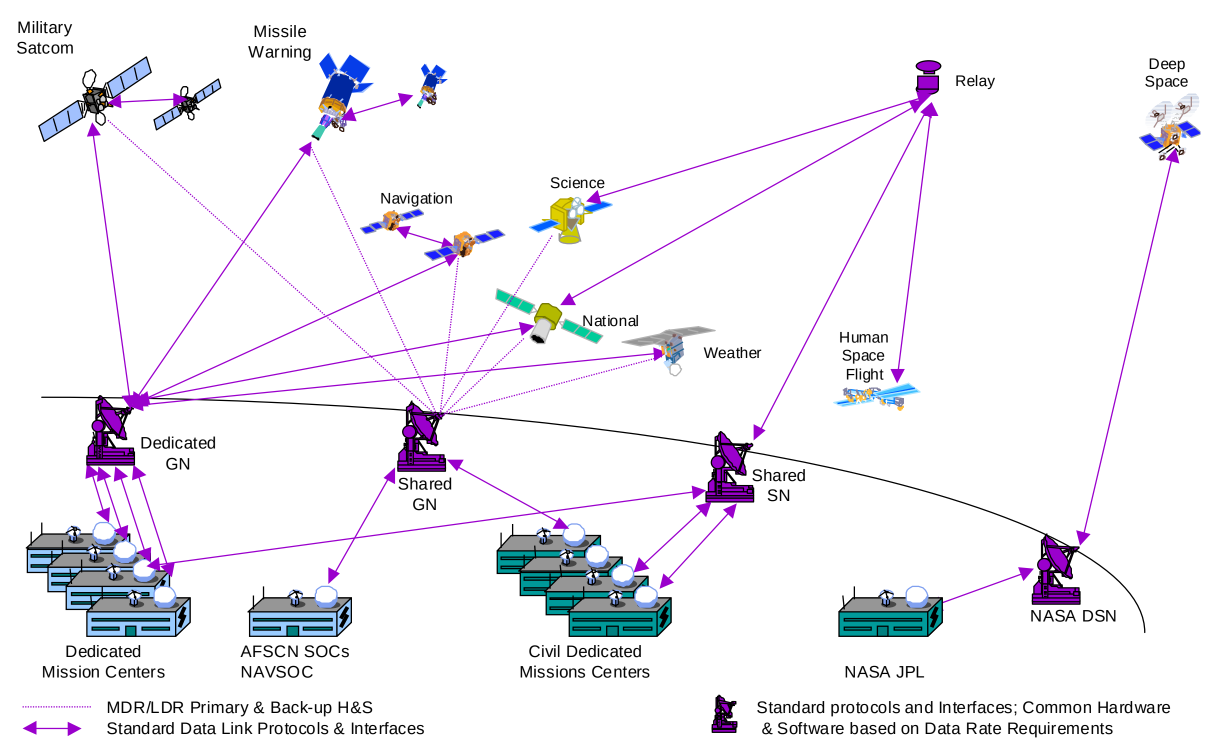
The Air Force is assembling a computer laboratory in which to investigate advanced concepts, including those for operational support of distributed satellite systems. Research includes:

- Satellite cluster management and control
- Fault detection software to correct satellite cluster anomalies
- Intelligent and collaborating software agents that replace traditional monolithic flight software and enable cross-satellite collaboration
- Advanced artificial intelligence techniques for efficient space and ground resource scheduling
- Reliable high-speed space-to-ground and space-to-space links to enable virtual satellite control and meet the high-volume data requirements therefrom
- Architectures that allow software to be easily migrated from the ground to the spacecraft after launch.

Selected project detail is tabulated in "Projected Applications," below.

Enabling Technologies *(Unconstrained)*

- Autonomous and adaptive algorithms for resource scheduling, mission planning, and mission execution
- Artificial/virtual intelligence (AI/VI), self-awareness, intuitiveness, automated recognition
- Human-machine interfaces and robotics
- Heterogeneous databases, software, integration, modeling and processing techniques
  - Advanced tools and algorithms for modeling and simulation (M&S)
- Satellite on-board data processing and storage
- Non-volatile random access memory
- Mass storage memory (including optical storage technologies)
- Laser/optical and/or microwave techniques for space-space, space-ground and space-air acquisition, tracking, and communications
- Radiation hardening and shielding of components
- Spacecraft laser and RF vulnerability mitigation techniques
- Precision time sources (10-ps timing accuracy) (atomic/laser clocks)
  - Network-centric communication synchronization techniques
- Plug-and-play hardware and software technologies
- Interoperability standards and protocols
- Encryption technologies
- Efficient solar cells and batteries (chemically or thermally generated electricity, such as thermionic power generation and thermo-electric conversion)
  - E.g., lithium ion/polymer hybrid batteries
  - Affordable solar cell materials and manufacturing
- Thermal management
  - Thermal distribution and control techniques
  - Cryocoolers
  - Other electronic cooling technologies
- Robust thruster design technology
- Advanced team training technologies.



Potential SatOps Architecture

Projected Applications

Capabilities and Characteristics	Project	Status	Agencies
Cooperative, autonomous, self-aware and self-healing; networked comms	• ***TechSat 21,*** experimental concepts for clusters of very low cost and weight microsatellites orbiting in close formation and potentially able to perform a variety of missions in and from space. Examples: – Microsatellite clusters that operate cooperatively to perform the function of a larger, single satellite – New concepts in space-based software intelligence to enable cluster-level C2, thereby allowing ground operations to task a cluster as an individual satellite and reduce SatOps complexity – New methods of space-time measurement and synchronization to manage the cluster and its microsat payloads.	Technology Concepts	Air Force
On-orbit servicing, rendezvous, proximity functioning capabilities	• ***Autonomous Space Transporter and Robotic Orbiter (ASTRO),*** the micro-shuttle vehicle of the ***Orbital Express*** – Autonomous space transporter and robotic orbiter concept to demonstrate feasibility of a servicing micro-vehicle permanently on orbit – Objective is a space vehicle that will conduct refueling and servicing operations autonomously, be able to access satellites at all orbital altitudes (LEO-to-GEO-to-Lagrangian points), and be able to perform significant plane changes – Development to include spacecraft-to-spacecraft interfaces to enable preplanned electronics upgrade, refueling, reconfiguration or resupply of consumables of one spacecraft by another.	Technology Concept (ATD Proposal)	DARPA
On-orbit servicing, multi-mission support	• ***Space Maneuver Vehicle (SMV)*** – High on-orbit maneuverability (>10,500 fps) for altitude and inclination changes – Standard payload bus for interchangeable ISR, space control and force enhancement missions – LEO/MEO station-keeping and rendezvous; GEO flyby – Flexible, moveable, recallable, runway-recoverable	Technology Concept	Air Force

GEO	Geosynchronous Earth orbit	GMTI	Ground moving target indication
ISR	Intelligence, Surveillance, and Reconnaissance	LEO	Low Earth orbit
MEO	Medium Earth Orbit	SAR	Synthetic aperture radar

Opportunities for Partnering

The Air Force Research Laboratory (AFRL) is a member of the Automation Technology for Space Operations Group (ATSOG), whose objective is to promote the insertion of automation technologies into space operations. ATSOG's membership includes all the NASA centers involved in space operations (manned and robotics) such as Johnson, Kennedy, Jet Propulsion Lab, Goddard and Ames, as well as the Naval Research Laboratory (NRL).

Potential collaborators for national security space operations include NASA/Johnson, the Jet Propulsion Laboratory (JPL), Aerospace Corporation (via the Air Force's Space and Missile Systems Center [SMC]), and the Naval Satellite Operations Center (NAVSOC).

6. Positioning, Navigation, and Timing

Area Description

Space-based navigation systems provide three-dimensional positioning data and a standard timing source to military, civil and commercial users worldwide, 24 hours a day. Precision navigation and timing provide targeting and geolocation information critical to coordinated and accurate force application by any platform in any medium. Today, the Global Positioning System (GPS) provides nearly worldwide coverage and constitutes a national asset.

The growing importance of space-based navigation systems to the national economy, as well as to a variety of non-military needs (civil aviation, emergency management, highway transportation, etc.), has created the need for significant upgrades and modifications to this space constellation. Additional civil signals that are separate from the military signals are one example. Meanwhile, on the military side there is a standing requirement for a "military-only" frequency. Thus, military interest in encrypted signals that are more easily denied to, and less easily denied by, an adversary during hostilities is another factor driving potential changes to the system.

Precise location and timing information, available in real-time, will be a prerequisite for effective force application in future military operations. As "sensor-to-shooter" capabilities mature, thereby accelerating ops tempo and the weapons-delivery cycle, updated targeting data will ensure the "precision" in precision-guided munitions (PGMs) and smaller target acquisition and launch errors for interceptors under ever-shortening information distribution cycles. These tactical advantages will, in turn, add confidence to the planning process, efficiency of force/weapons allocation, and effectiveness in overall operations.

Current plans call for modifying the last 12 of the third-generation GPS satellites, Block IIR, by adding more power, a second civil signal and a new, more robust military signal. The fourth-generation satellite, Block IIF, is under development. This spacecraft will have many improvements over its predecessors to include longer life, improved reliability, more power, and a third civil signal capable of satisfying safety-of-life requirements for civil aviation. Plans are being formulated to conduct an architecture study for the next-generation satellite navigation system, GPS III, capable of meeting military and civil needs through 2030.

Mission Area Objectives

- Continuous global coverage in all environments
- Continuous coverage of space (to GEO x 2)
- Improved positional and timing accuracy
- Operation in a navigation warfare environment (robustness)
- Denial of unauthorized third-party use
- Timely warning of bad data or failures

Supporting Capabilities

On-orbit reconfigurability/upgrades to accommodate changes in GPS requirements

Satellite RF interference/vulnerability mitigation

Software to provide continuous status reporting

Encryption and on-board software functions

Current Technology Initiatives *(Highlights of Current FYDP)*

Near-term activities seek to upgrade the GPS to a jam-resistant military waveform and to develop navigation warfare technologies. This will include work to ensure that the new waveform is resistant to electronic attack without interfering with the operation of current dual-use equipment.

System performance of new-technology spaceborne atomic clocks for ranging and timing synchronization will be demonstrated by non-interference introduction on the spacecraft.

Selected project detail is tabulated in "Projected Applications," below.

Enabling Technologies *(Unconstrained)*

- Technology to achieve increased location accuracy
- Improved precision time sources (10-ps timing accuracy) (atomic/laser clocks)
  - Network-centric communication synchronization techniques
- Technologies for receivers, waveforms and antennas to enable:
  - Penetration of clouds, obscurants, foliage, and terrestrial structures
  - Control/adjustment of signals, power, and frequencies to enable better signal penetration and jam-resistance
- Radiation hardening and shielding of components
  - Lightweight radiation-hardened materials
- Reprogrammable radios and other electronics system components
  - Field programmable gate array (FPGA) technologies
- More efficient solar cells and batteries (chemically or thermally generated electricity, such as thermionic power generation and thermoelectric conversion)
  - E.g., lithium ion/polymer hybrid batteries
  - Affordable solar cell materials and manufacturing
- Algorithms and coding techniques for software and hardware
  - Waveform error correction
  - Encipherment techniques
  - Navigation algorithms
- Inertial guidance techniques
- Pointing and tracking (e.g., laser pointing)
- Software technologies, programming environments
- Simulation modeling tools.


GPS Block IIR


GPS Block IIF

Projected Applications

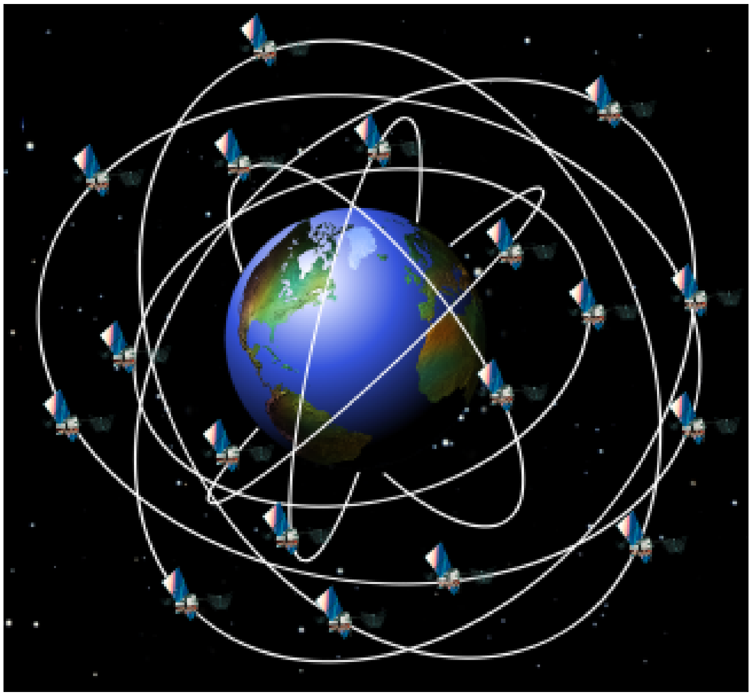
Category	Activities	Status	Agencies
Advanced waveform technologies with anti-jam capabilities	- ***Military waveform studies/assessments*** – Initial assessments have been conducted and preliminary results delivered – Other studies are ongoing, with future studies planned	Technology concepts	Air Force
	- ***Current and future military waveform user equipment with anti-jam capabilities*** – Ongoing, with deliveries (to all Services)	Technology development and delivery	All Services
Application of geolocation technologies to all DoD systems	- ***Advanced GPS Inertial Navigation Technology*** – Brassboard delivery ~ FY02	Development program	Air Force
	- ***Joint Precision Aircraft Landing System***	Dev't pgm	Air Force
	- ***New technology spaceborne atomic clocks*** – To maintain/increase system performance and operability	Technology concept	GPS JPO and Navy

Opportunities for Partnering

As a national resource, GPS is managed by the Interagency GPS Executive Board (IGEB), co-chaired by the DoD and Department of Transportation (DOT). IGEB members include NASA and the JCS, as well as other Federal agencies.

As a joint program, the Army, Navy and Air Force have been working together to develop and improve GPS system and user equipment since its inception. GPS has also been adopted by a growing number of civil, commercial and scientific users throughout the world. A large number of equipment vendors are offering literally hundreds of types and models of GPS receivers for sale on the commercial market. The vulnerability of commercial receivers to jamming makes it impossible to use them as-is for military operations. Nevertheless, the highly competitive commercial marketplace has introduced forward-leaning receiver technologies that have found their way into latest generation of military GPS user equipment.

In addition, there is an opportunity for certain military aircraft operating in the National Airspace System to use off-the-shelf (OTS) equipment to be compatible with civilian air traffic control systems that use GPS. The DOT's Federal Aviation Administration (FAA) is lead agency for the development and implementation of those applications.



GPS Constellation

7. Command, Control, and Communications

Area Description

Command, Control and Communications (C3) are the key to managing the battlespace and exploiting information superiority as enablers of all other operational and support missions. Effective C3 assures situational awareness and provides the ability to control terrestrial, aerospace and missile forces at all levels of command. It focuses on getting the right information to the right users at the right time. The C3 infrastructure supports the exercise of command and control (C2) authority and direction over assigned forces and includes the processing, analysis, use and dissemination of information to shape and dominate the battlespace. Maintaining aerospace superiority will enable the space-based portions of the C3 architecture to continue to service the operator as effectively as they have done to date.

Current DoD communications satellites and other links provide military forces with high-capacity, near-real-time voice, data and video communications, and assured information. These systems provide the essential conduits for information vital to the full range of successful military operations. The Satellite Communications (SATCOM) network provides near-global coverage and flexibility. Warfighters' access to mission-related information allows them to make near-real-time decisions critical to successful operations. No other command and control system in the world must meet the same level of simultaneous requirements of security, mobility and surge envisioned for these C3 systems.

Critical space C3 operational functions and their enabling technologies include automated planning and collaborative decision tools, automated satellite operations, real-time aerospace systems integration to yield a common situational picture, integrated data fusion and wargaming, and near-real-time monitoring and assessment. Moreover, the increasing interaction and interdependence of C3 and ISR (themselves evolved combinations) — via their increasing reliance on computers — have led to their current recognition as a functional continuum: command, control, communications, computers, intelligence, surveillance, and reconnaissance, or C4ISR.

For the future, technology programs are in place to yield next-generation capabilities as summarized in this section. For the near and mid-terms, emphasis is on specific programs; for the far term, emphasis extends to generic technologies and capabilities to meet broader concepts and emerging needs. To lay the groundwork now for the future C3 and C4ISR environment, additional emphasis is needed in the areas of dynamic C2 and development of the Global Grid, as well as flexibility of resources to support the emerging mission of Information Operations.

Mission Area Objectives

Command and Control	Communications
• Monitor and assess global conditions and events; maintain a common situational picture • Plan military operations (joint, coalition) • Execute military operations (joint, coalition) • Allocate, task, command and control one's own resources • Collect, process and fuse data; store, retrieve and/or distribute information to warfighters • Ballistic Missile Command, Control and Communications (BMC3) functions: – For national forces – In support of theater forces	• Global, space-based, high-bandwidth, high-data-rate (HDR), robust, secure and seamless communications for national security requirements • Global high-bandwidth telecom infrastructure • Seamless data collection and information access • Fully integrated, interoperable, coalition-based communications network

Supporting Capabilities

Advanced mission planning functions

Universal protocols

Hardware, software and procedural standards to assure requisite interoperability (of both systems and processes)

Modularity/serviceability to keep pace with technology

Advanced C2 networks/architectures

On-orbit cross-links

Satellite laser and RF interference/vulnerability mitigation

Higher carrier frequencies

Greater information channel capacity

Encryption and jam-resistance

Advanced system status, diagnostic and healing functions

Advanced force monitoring and status reporting functions

Space-based internet

Broadcast information

Current Technology Initiatives *(Highlights of Current FYDP)*

Near-term S&T projects and activities are focused on the attainment of robust C4ISR systems with abilities to:

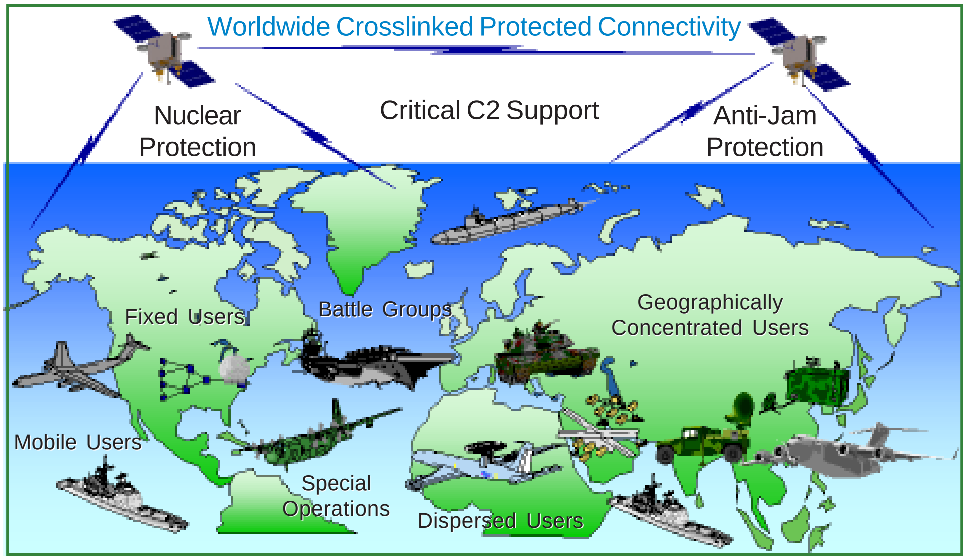
- Provide a common situational picture
- Include a suite of integrated, automated planning tools
- Provide near-real-time monitoring and assessments
- Include an integrated wargaming capability
- Exercise more precise and reliable system timing to enable high-rate data transfers and fusion
- Integrate autonomous (ground and spacecraft) capabilities into general operations.

Key projects include continuing work on:

- A high-bandwidth space vehicle data bus to meet ISR needs for greater throughput and near-real-time timelines, and high-bandwidth burst data to airborne C2 nodes
- Advanced laser technologies to provide acceleration-immune frequency standards.

In turn, these capabilities will:

- Improve global satellite communications coverage, flexibility and robustness
- Enhance interoperability with commercially available communications systems
- Facilitate C3I link upgrades and automated operations
- Facilitate continuous surveillance capability (long-dwell connectivity and fusion of multiple satellite constellations)
- Reduce data collection, processing and dissemination times, which will especially benefit ISR, Space Control, and future Force Application functions.

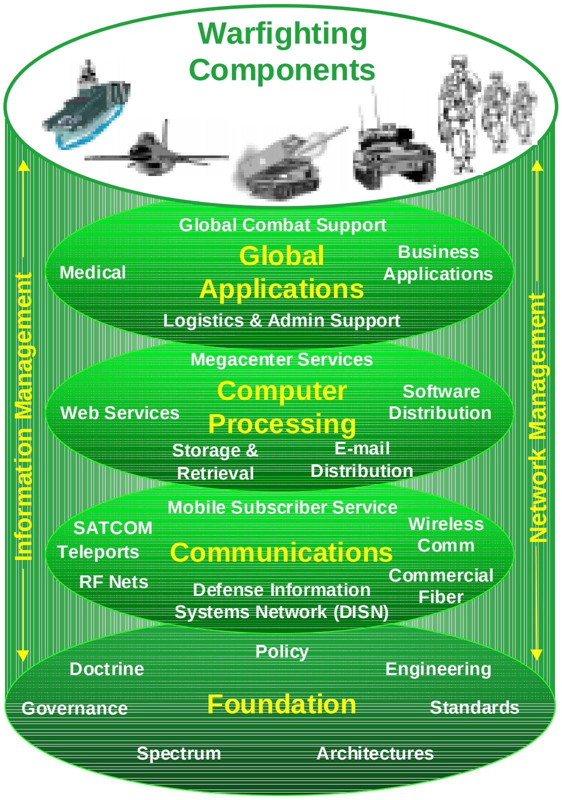


Advanced Extremely High Frequency (AEHF) Sytem Concept

Selected project detail is tabulated in “Projected Applications,” below.

Enabling Technologies *(Unconstrained)*

- Technologies to protect/secure facilities and structures (materials, power, cooling, reconfigurability, shielding)
- High- and low-temperature superconductor device technology to enable frequency hopping, advanced spread spectrum
- Encryption technology (e.g., quantum cryptography and computing)
- On-orbit dimensional control and vibration mitigation techniques
- Improved precision time sources (10-ps timing accuracy) (atomic/laser clocks)
    - Network-centric communication synchronization techniques
- Laser/optical and microwave communications and associated acquisition/tracking/pointing for space-space, space-air, and space-ground applications
- Advanced waveforms for efficient, robust links
- Self-forming, self-healing terrestrial networks
- Cross-cueing, dynamic database fusion, synergy of imagery, spectral and signal functions, phenomena & information
- High-volume/speed processing, storage and display technologies
- Increased satellite onboard data processing and storage for timely data delivery
- High-performance RF front ends
- Efficient analog-to-digital (A/D) converters
- Reprogrammable radios and other electronics system components
    - Field programmable gate array (FPGA) technologies
- Advanced antennas
    - Improved performance land/shipboard/airborne SATCOM antennas
    - Robotic deployment and self-assembly techniques for very large antennas
    - Large, lightweight, electronically steerable antennas
- Efficient transmit/receive (T/R) modules
- Radiation hardening and shielding of components
- More efficient solar cells and batteries (chemically or thermally generated electricity, such as thermionic power generation and thermoelectric conversion)
    - E.g., lithium ion/polymer hybrid batteries
    - Affordable solar cell materials and manufacturing
- Human system interfaces for decision-making
- Intelligent software agents
- Human system interfaces for information exploitation and decision-making
- Control center technologies
    - Write once read many (WORM) storage
    - Archival mass storage.



Global Information Grid

Projected Applications

Category	Project / Activity	Status	Agencies
Data Fusion	• Joint Battlespace Infosphere (JBI)	M&S	Defense-wide
Sensor Fusion	• Moving target exploitation • Sensor-to-decision-maker-to-shooter technologies	M&S Technology	Air Force Air Force
Global Warfighter Decision-Making Tools	• Joint Aerospace Tasking Order (JATO) • Joint Targeting Toolbox (JTT) • Collaborative Engineering Environment (CEE) • The Multi-Sensory C2 Advanced Technologies (MCCAT) • Global Awareness Virtual Testbed (GAVT)	M&S and Technology development	Defense-wide
Effect-Based Operations	• Strategy-to-task software algorithms • Multiple scenario generation and potential outcomes	Technology development	Defense-wide
Advanced Communi-cations	• Global Grid infrastructure (to underlie and support information products) • Configurable Aerospace Command Center (CACC)'s optical intersatellite links (OISL) and lasercom to Airborne Command Posts (ACPs) and enroute operations centers • Intelligent network management technologies	Architecture and Network technology development	Defense-wide

Opportunities for Partnering

The military Services will continue to work with each other and with other organizations such as DARPA, NRO, BMDO, NASA, NOAA, NIMA and supporting industry to provide the joint C3-C4ISR space capabilities needed to meet existing operational requirements and projected needs. Requisite technologies include those to support automated/expert system satellite operations, real-time integration of aerospace systems, automated planning and collaborative decision tools, and development and distribution of a common situational picture from order of battle (OOB) through battle damage assessment (BDA). This capability will involve specific technologies and tools associated with automated mission planning and satellite operation, multi-source data fusion, and near-real-time monitoring, assessment, and display.

Specific Service partnerships include Air Force collaboration with NASA's JPL for optical communications, with BMDO for secure optical C2 technology, and with the National Institute of Standards and Technology (NIST) and the Naval Observatory for laser clocks. The Air Force will also continue to work with BMDO, NASA and JPL on laser communications, precision pointing, and advanced lasers. Work with the GPS Joint Program Office (JPO) on future timing technology includes the merging of navigation and communications. Under the Aerospace Command and Control, Intelligence, Surveillance and Reconnaissance Center (AC2ISRC) and with the Air Force as lead, the other Services and Defense Agencies will incorporate their data to yield a composite Data Fusion Roadmap.

8. Intelligence, Surveillance, and Reconnaissance

Area Description

Joint Vision 2020 depends on information superiority for virtually every aspect of military activity. The combination of intelligence, surveillance and reconnaissance (ISR), together with real-time communications and information processing technologies, is its enabler. It involves primarily electronic systems to find, watch and collect data from sources and provide it as information to users.

ISR permeates almost every area of national security activity, from peace through war. It involves techniques and systems operating both passively and actively in all operational environments from subsurface to space. A key benefit of this capability, from data collection through warning to its timely use by warfighters, is political and/or military success — through knowing more and knowing it sooner than opponents.

ISR includes information about: all operational threats to U.S. and Allied lives, assets, and interests; military force movements; all spacelift vehicles, missile systems (mobile or fixed), and spacecraft; all aircraft types, land-operating systems, and surface/submerged maritime vessels; nuclear detonations; threats to friendly space assets; chemical and/or biological weapons; and other significant space, surface and subsurface events. ISR activities support the intelligence and warning needs of all Services, the National Command Authorities (NCA) and other government agencies, support U.S. and Allied operations, and assist in international treaty monitoring.

The major goal of ISR is success through information dominance. Increasing demands for precise, finished intelligence on a wide range of defense intelligence requirements strain the resources currently available. Space-based intelligence collection capabilities have matured into powerful and reliable systems, able to meet a much larger fraction of the validated user requirements than ever before. Under today's exploitation and dissemination paradigms, our available personnel, communications and hardware cannot fully utilize the available data. Thus the Intelligence Community is pursuing a full range of technologies not only to enhance the collection of necessary data but also to examine new ways to produce and disseminate the information our users need. This approach includes:

- New and potentially revolutionary collection systems
- New analysis and dissemination methods and paradigms
- Significant improvements in data processing, storage-retrieval, and request-redistribution functions.

An evolving concept to deal with the multiplicity of evolving ISR and related information distribution concepts is contained in the term "infosphere." This construct involves information collection and integration across all activities (fusion), with follow-on processing to tailor its disseminated products for specific warfighters and other users.

Specific concerns and evolving needs include the following:

- The orbits of space-based ISR systems are currently predictable. However, if (per SatOps concepts) it becomes possible to maneuver them at will, an adversary would find it much more difficult to avoid detection or to interfere with them. Further, if they could be refueled on-orbit, they could be maneuvered to counter adversaries' operational planning or direct attack, without shortening mission life.
- Infrared detection of missile launches remains a key element of tactical warning; hence DoD's support for the Space-Based Infrared System (SBIRS) program as a replacement for the aging Defense Support Program (DSP) warning satellites.
- A space-based radar capability is needed to enable continuous (24-hour) full-global coverage. Benefits would include precision maps, detection and continuous tracking of sea, ground and air moving targets, and accurate real-time determination of orders of battle (OOBs).

- Proliferation of nuclear/biological/chemical (NBC) weapons requires counterproliferation technologies and capabilities as soon as practical.
- Transition from legacy systems to new ones, such as elevation of Airborne Warning and Control System (AWACS) and Joint Surveillance and Target Attack Radar System (JSTARS) capabilities to space and the increasing use of unmanned aerial vehicles (UAVs) and space sensor platforms, is needed to meet the ISR needs of warfighters everywhere.

Mission Area Objectives

- Global day/night all-weather surveillance and reconnaissance (as basis for situational awareness)
- Timely threat warning infomation (land, sea, air, and space)
  - Detect, track and ID ballistic and cruise missiles, and fixed or moving objects, signals or signatures, worldwide
  - Locate missile launch points, predict their impact points
- Real-time detection, ID, characterization and geolocation of fixed surface/subsurface and mobile targets:
  - Target set detection/surveillance/monitoring/tracking
  - Information on camouflaged, concealed and deceptive (CC&D), deeply buried and other "hard" targets
  - Ability to defeat attempts to schedule activities to avoid detection
- Information on NBC weapons and events
- Intelligence planning, tasking, cross-cueing, fusion, processing, and dissemination

Supporting Capabilities

Modular spacecraft designs for efficient integration, launch and on-orbit “plug and play”
Tactical agility with minimal involvement of ground support personnel
On-orbit propulsion to maneuver spacecraft at will
Higher data rate communications and information processing for fixed and mobile users
Flexible, multi-level information security   On-board processing
Automated cross-cueing   Efficient space-to-space crosslinks
Adaptive, autonomous sensors   Continuous surveillance/long-dwell coverage
Systemic counter-countermeasures
Elevation of AWACS and JSTARS capabilities to space
Surveillance platforms with ultra-lightweight deployable optics and antennas
Combined GMTI and SAR imaging from space
Constellations to provide global coverage   Space-based NBC materials detection
Advanced multi-, hyper- and ultra-spectral information content collection and exploitation
Enhanced target-to-background contrast ratios, target signature characterization, and modeling
Improved characterization of hardened and deeply buried targets

Current Technology Initiatives *(Highlights of Current FYDP)*

Near-term focus is on multi-mission technologies that have application to both air and space surveillance missions. Two such areas are hyperspectral imaging (HSI) and space-based radar (SBR) development.

The HSI program is developing day/night HSI technology capable of rapid precision threat identification and targeting of space, air and surface targets with a longer-term space goal of HSI systems on orbit as part of a national HSI architecture. Technologies include high-resolution focal planes, long-life cryocoolers, on-board signal processing, spectral exploitation algorithms, atmospheric compensation (both reflective and emissive), generation of spectral databases of targets and backgrounds, data fusion technologies, and high-performance computing and displays.

Per Congressional guidance on SBR development, both specific and generic technologies are being pursued:

- Specific projects applicable to airborne and ground moving target indication (AMTI/GMTI) SBR concepts include: affordable, lightweight active transmit/receive antenna modules, spacecraft power management and distribution, and high-efficiency microwave transmit and receive devices
- Generic technology areas extensible to SBR functions include ISR modeling and simulation, bistatic clutter characterization, space-time adaptive algorithm development, improved front-end noise rejection for RF systems, analog-to-digital converters, and advanced RF systems.

The NRO is continuing to develop low-cost Electronically Scanned Array (ESA) technology initiated under the former joint Discoverer II program. In addition, the NRO is examining opportunities and concepts of operations for radar-related experiments and demonstrations using currently available assets.

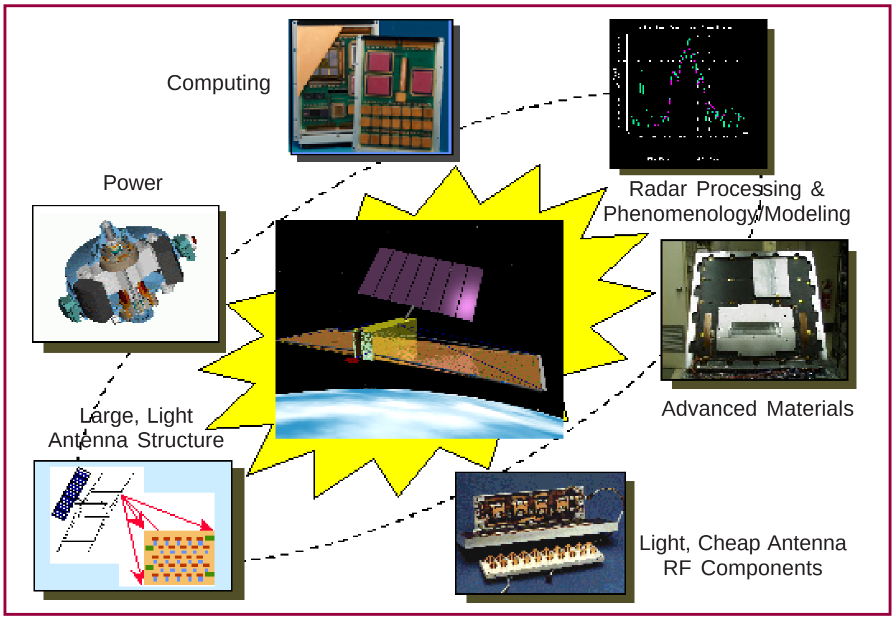
Additional projects and detail are tabulated in “Projected Applications,” below.

Enabling Technologies *(Unconstrained)*

- Autonomous, adaptive, self-training, error-correction and real-time planning algorithms for tasking, mission planning/management, target ID/tracking and battlefield learning, and data compression, processing, exploitation, and dissemination
- Automated cross-cueing, dynamic database fusion, geographic information systems (GIS), and synergy of imaging, spectral and signal functions, phenomena and information technologies
- Increased satellite on-board data processing and storage for timely data delivery
  - Non-volatile random access memory
- ISR modeling and simulation
- Miniaturized, scalable, power-efficient electronic components and mechanisms
  - E.g., fiber optics, optoelectronics, photonics, microelectromechanical systems (MEMS)
  - E.g., high-temperature superconducting electronics to eliminate need for sensor cryocooling
- Large, lightweight support structures and materials
- Shape memory techniques and alloy materials
- Active and passive electromagnetic spectrum devices to direct, disseminate, focus and transmit — as well as to detect, extract, sense and receive — energy:
  - Heat (infrared [IR])
  - Visible light
  - Radio frequency (RF)
- Fusion processing software algorithms
- Increased sensor range and sensitivity technologies
  - Atmospheric and radiant background characterization, modeling, and processing

  - Improved atmospheric compensation and target classification algorithms for multi-spectral/hyperspectral image processing
- Exploitation technologies for bistatic phenomenology of targets and clutter characteristics
  - Bistatic space-time adaptive processing algorithm validation
  - True time-delay processing
- Multistatic time and frequency correlation, signal processing, and data fusion
- Advanced target detection technologies
  - E.g., acousto-optical detection and spectral signature exploitation (to see through clouds)
- Non-intrusive inspection technology
- Advanced electro-optical (EO) technology
- Hyperspectral sensing: improved low-power high-capacity on-board processors
- Hyper- to ultra-spectral imagery (HSI-USI) sensors (100s to 1000s of bands)
- Advanced IR technologies
  - Quantum cascade and interband semiconductor IR laser sources
- Multispectral/hyperspectral and very short wavelength infrared (VSWIR) sensors/imagers
  - Multi- to ultra-spectral detector materials, processes, and manufacturing
- Large focal plane array (FPA) detector materials science and manufacturing
  - E.g., staring FPAs for multispectral detection, read-out integrated circuits (ROICs), quantum well IR photodetectors (QWIPs)
- Advanced small, high-capacity, space-qualified cryocoolers
  - More efficient on-orbit storage of cryogenic hydrogen
  - More efficient infrared applications
  - Advanced regenerator/phase-change materials
- Low-power laser atmospheric compensation and beam control
  - Optical phase conjugation
  - Adaptive laser optics
  - On-orbit dimensional control
  - Jitter and vibration management
- Advanced acquisition, pointing and tracking techniques
- Space-based high-resolution optical/radar/multi-spectral imaging technologies (active or passive)
- Space-based laser, lidar or relay mirrors for remote optical sensing
  - Large-aperture, lightweight, modular, deployable membrane mirrors/optics, and support structure materials
- Durable thin-film substrate/membrane/coating materials, processing, and manufacturing
- Nonlinear optical materials for specialized sensors and biological/chemical threat detection
- Optically efficient and variable-emittance mirror coatings
- On-orbit servicing of mirror coatings
- Advanced RF technology
  - Photonics for phase-shifting and beam-forming
  - Spectral analyzers and algorithms
  - Digital RF memory (DRFM)
- Advanced synthetic aperture radar (SAR)
  - E.g., inverse and interferometric SAR
- Advanced automatic target recognition (ATR), moving target indication (MTI), and orbital dynamics processing algorithms
- Large affordable, lightweight RF reflectors and antenna designs
  - E.g. inflatables, deployable array-fed reflectors
  - E.g. solid state phased array electronically steerable antennas
  - Higher strength-to-weight and composite materials and designs
- Radar components with higher frequency and power output
  - High-temperature semiconductor materials for RF/radar components

  - W-band low noise vacuum electronics
  - X-band solid state (wide bandgap) components
- Technologies for receivers, waveforms and antennas to enable:
  - Penetration of clouds, obscurants, foliage, and terrestrial structures
  - Control/adjustment of signals, power, and frequencies to enable better signal penetration and jam-resistance
- Advanced, lower-cost, higher-frequency/bandwidth transmit/receive (T/R) components
- Improved front-end noise rejection for RF systems
- Advanced mixers and analog-to-digital (A/D) converters
- Advanced signal excision techniques
- Laser/optical communications and associated acquisition/tracking/pointing for space-space, space-air, and space-ground applications
- Non-volatile memory optical computing/communications
- Advanced laser and microwave communications technologies for space-space, space-air, space-ground links
  - Advanced netting and encryption technologies
- Reprogrammable radios and other electronics system components
  - Field programmable gate array (FPGA) technologies
- More efficient solar cells, batteries (chemically or thermally generated electricity, such as thermionic power generation and thermoelectric conversion)
  - E.g., lithium ion/polymer hybrid batteries
  - Affordable solar cell materials and manufacturing
- Radiation hardening and shielding of components
  - Radiation-resistant composites and associated materials
  - High-temperature and radiation-resistant electronic materials
  - Flash radiation-hardened digital memory (e.g., SiC)
- Satellite laser and RF interference/vulnerability mitigation
  - Bi-/multistatic techniques
  - Synthetic/virtual apertures
- Isothermality technologies
- High heat-dissipating thermal doubler/plane materials
- Advanced effects phenomenology
- Human-system interfaces for information exploitation and decision-making
- Control center technologies
  - Write once read many (WORM) storage
  - Archival mass storage.



Space-Based Radar (SBR) Concept

Projected Applications

These unclassified technology and program listings represent a major portion of ISR technology investment. Other initiatives, programs and collaborations are classified.

Category	Project / Activity	Status	Agencies
Advanced Target Detection and Imaging	• ***Infrared (IR) technologies*** for target detection, e.g.:		Air Force
	– Space-Based Infrared System (SBIRS) -High	EMD	
	– SBIRS-Low	Dem/Val	
	• ***Space-Based Radar (SBR) technologies***	Technology developments	Air Force (lead) DARPA, NRO, Army
	– Airborne moving target indication (AMTI)		
	– Ground moving target indication (GMTI)		
	– SBR with GMTI and SAR imaging (space-based sensor support to operations)		
	• ***Hyperspectral Imaging (HSI) projects*** to address HSI utility issues:	Technology demonstrations	
	– Warfighter I		Air Force
	– EO-1		NASA
	– Multispectral Thermal Imager (MTI)		DOE
	• ***Space-Based Laser (SBL) Imaging***	Concepts, experiments, developments	Air Force
	– Lighter, cheaper, stable, large space optics		
	– On-orbit resupply concepts		
	• ***Space Maneuver Vehicle (SMV)***	System concept	Air Force
	– Tailored ISR constellations		
	– Interchangeable ISR payloads		
Platform Technologies	• ***Generic spacecraft projects***	Concepts, experiments, developments	(Several)
	– Radiation-hardening technology programs		
	– Processor development activities		
	– Battery development activities		
	– (See **SatOps** concepts and projects		
	– *(Other classified activities)*		
Information Management	• ***Real-time global awareness***	Concepts, experiments, developments	Government interagency activities (DoD, NASA, others)
	– Consistent battlespace picture		
	— To provide a common operational context		
	– Automatic target recognition (ATR)		
	– Broadband crosslinks and downlinks		
	— To support data processing		
	– Tactical display feeds		
	— To disseminate ISR products and services		
	– Future information, fusion and dissemination architectures		
	– Information exploitation technologies		

DemVal Demonstration/Validation acquisition phase

EMD Engineering and Manufacturing Development phase

Opportunities for Partnering

The DoD, DOE and NASA Space Technology Alliance (STA) coordinates development of affordable technologies with applications to space.

The National Security Space Architect (NSSA) is developing, coordinating and integrating DoD and IC space architectures. Meanwhile DoD, civil and commercial systems need to be integrated to achieve required capabilities at affordable cost, to include:

- Integration of NRO sensor and communications systems in theater operations
- Cooperation with other agencies, such as NOAA for weather satellites
- Coordination among Service space activities
- Finding best ways to use commercial space capabilities.

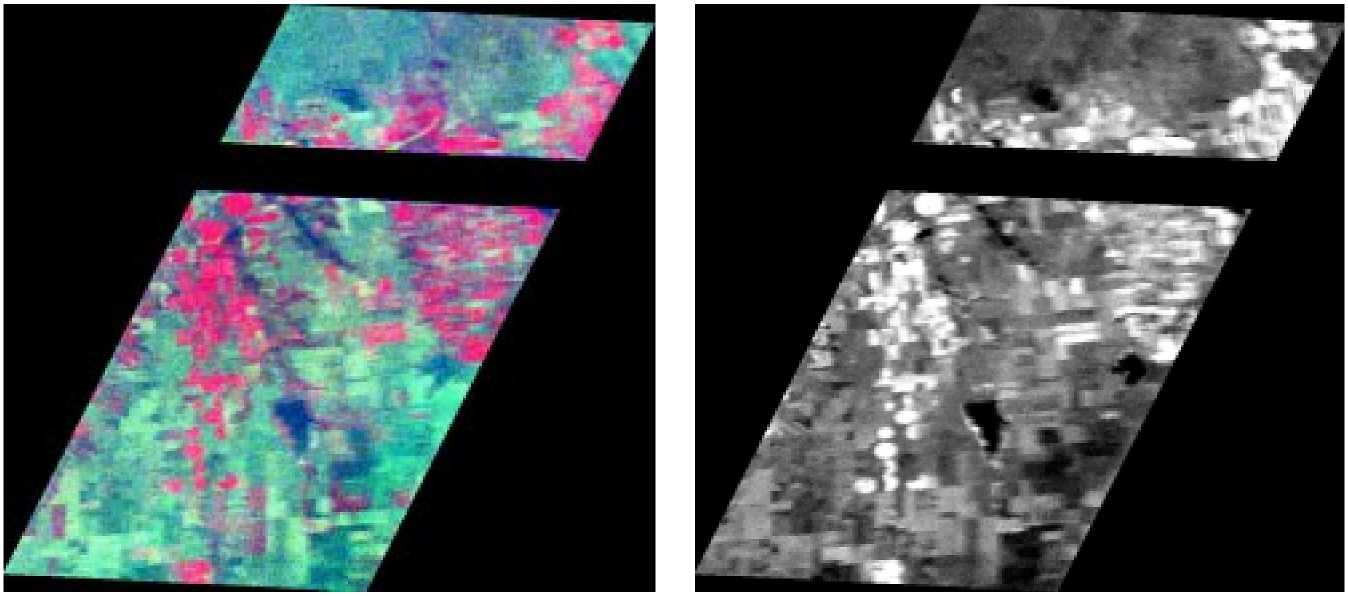
Air Force work to make large space optics lighter, stable and cheaper may also benefit NASA and other space systems and concepts.

The DoD and IC are beginning to share the burdens of basic technology development and costs of the industrial infrastructure with commercial industry (e.g., the NRO is already using a commercial bus for some satellite systems). Lessons learned from mass manufacturing of commercial satellites will benefit both government and industry.

In the area of commercial remote sensing, NIMA acquires commercial imagery from multiple vendors both for geospatial data production and for peacetime and crisis applications. NIMA will also acquire unclassified imagery from new high-resolution commercial remote sensing systems with enhanced spectral capabilities. A joint government-industry team will identify the best data acquisition approach for the future.

Meanwhile, broadband demands of an SBR system and similar anticipated commercial systems may result in a very difficult frequency allocation challenge. Here, the DoD should use commercial industry's influence in the international arena to achieve common solutions.

MightySat II.1 Fourier Transform Hypersepectral Imager (FTHSI):
First Image From Space (Georectified)



False Color IR Image (3 bands)

Grayscale Image (λ =775)

9. Environmental Monitoring

Area Description

Environmental support for land, sea and air operations includes the day-to-day provision of space products and services to operational forces. These regional and local descriptors are key elements by which warfighters can use the natural or changing environment as part of their operational planning and execution. Thus, improved knowledge and prediction of the physical environment affecting the battlespace can be leveraged for mission success. Technological advances in Service and Defense Agency systems and techniques for global environmental characterization and prediction, and in their associated communications and data processing capabilities, are steadily improving the contributions of environmental monitoring services and products to the full spectrum of terrestrial military operations.

By comparison, space weather services and environmental characterization capabilities are relatively limited, but are expanding rapidly to keep pace with expanding space operations per se. A number of new technologies and operational capabilities are being deployed in the next few years to yield dramatic improvements in space weather monitoring and prediction and space environmental research. Many of these advances require routine access to space.

Environmental monitoring and the development of geospatial information for national security purposes rely on defense, civil and commercial space capabilities. The government both buys and provides space-generated terrestrial imagery and other information products, while customers for military space-generated information and services include such agencies as: the Departments of Agriculture (DOA), Commerce (DOC), Energy (DOE), Interior (DOI), and State (DOS); NASA; the Federal Aviation Administration (FAA) and Federal Communications Commission (FCC); the Arms Control and Disarmament, Environmental Protection, and U.S. Information Agencies (ACDA, EPA, and USIA); the National Science Foundation (NSF) and Smithsonian Institution; and a host of other civil and commercial organizations.

This mission area includes the traditional missions of Mapping, Charting, and Geodesy (MC&G). Within the DoD, the joint Defense Meteorological Satellite Program (DMSP), GPS, GEOSAT, NRO programs, National Imagery and Mapping Agency (NIMA) products and meteorology and oceanography (METOC) programs provide comprehensive weather, mapping, intelligence, and environmental surveillance, monitoring and forecasting support worldwide. Four space-reliant disciplines directly protect fighting forces and support facilities from adverse conditions and enable operational advantage by exploiting the physical environment to optimize the performance of platforms, sensors, and weapons. These disciplines — METOC, geospatial information and services, precise timing, and astrometry — provide an assessment of the impact of natural phenomena on weapon systems around the world and contribute to other functions (e.g., navigation, geolocation, flight safety, search and rescue) in the process.

Concurrently, as space-based capabilities become increasingly important to terrestrial operations, observing, understanding and predicting the naturally harsh space environment itself is becoming increasingly important to continued operations in all domains. This "space weather," such as extremes of heat and cold, as well as radiation effects and collisions with space debris, can cause equipment failures and outages. Similarly, geomagnetic and ionospheric disturbances can disrupt even sophisticated wireless communications and navigation networks, interfere with global surveillance and information integration, and impede the proper functioning of sensors and networks that detect and track aircraft, missiles, and spacecraft.

From a technology-driver viewpoint, the needs are emerging as two-fold: on the one hand, space-based monitoring of the terrestrial environment requires ever more and more sophisticated space-based sensor systems and their associated processing and communications functions. (For example, the ability to observe and forecast atmospheric conditions with greater accuracy and timeliness, especially cloud cover and other obscurants over prospective target areas, would greatly support strike operations.) On the other hand, space-based systems (for all missions) need to monitor and be resistant to the effects of their own space environment. Even temporary outages (e.g., from geomagnetic or ionospheric effects) can jeopardize the assured information flow needed by military forces and by civil and commercial customers alike.

Mission Area Objectives

Advanced understanding of the environment from observation to prediction

Timely, high-quality real-time global weather data to operators

Three-dimensional (3D) characterization of ocean and land topography and the atmosphere

Global METOC and Earth remote monitoring (ERM) coverage

Differentiation of manufactured from natural phenomena and signatures, classification/identification, and timely change recognition

Improved capabilities to observe, model and forecast space environmental parameters

Earlier detection and assessment of space weather effects

Increased integration of space with terrestrial sensors
E.g., unattended ground sensors (UGSs), unmanned aerial vehicles (UAVs)

Remote sensing of chemical effluents, fuel spills, atmospheric pollutants

Supporting Capabilities

Higher data rate on-board processing with faster refresh rates for METOC and ERM data sets

Improved spatial resolution of METOC and ERM data

Characterization of micrometeoroids and debris in orbits of military relevance

Exploitation of environmental impacts on sensors, weapons, systems, and platform performance

On-orbit monitoring of Van Allen Belt fluctuations

Detection and characterization of solar coronal events

Satellite laser and RF interference/vulnerability mitigation

Current Technology Initiatives *(Highlights of Current FYDP)*

Current projects address both the terrestrial environment, where most military operations will continue to take place, and the space environment, where increasing types and numbers of military functions will take place in the 21st century.

Terrestrially oriented technology programs continue to support space-based weather observation and forecasting, mapping, intelligence, environmental surveillance and forecasting, and both atmospheric and oceanic characterization operations worldwide. Their programs include DMSP, GPS, GEOSAT, specific NRO programs, NIMA products, and METOC functions. In addition, advanced monitoring systems include the developmental National Polar-orbiting Operational Environmental Satellite System (NPOESS), in which the Navy WindSat program is providing risk-reduction efforts for the:

- NPOESS Conical Microwave Imaging Sounder (CMIS) program
- Naval EarthMap Observer (NEMO)
- Indian Ocean METOC Imager (IOMI) program.

Space environmental monitoring and characterization projects include:

- The IOMI program to demonstrate critical sensor technologies for future civil and military weather systems that could greatly improve global weather forecasting by covering the broad Indian Ocean area
- A space weather S&T program of basic research through prototype development of operational sensors, models, and tailored products
- A program to provide real-time alerts and up to 1-hour forecasts of scintillation impacts to UHF SATCOM will be expanded from 4 to 10 sites and upgraded to include L-band scintillation warning for GPS navigation links

- Development of the Communication/Navigation Outage Forecast System (C/NOFS) sensor to provide GPS with 4-6 hour forecasts of scintillation outages
- Validation of a program currently used to specify global electron and neutral density profiles, plus upgrades to ground-based ionospheric sensors and algorithms to assimilate both ground- and space-based data into global electron and neutral density forecast models
- The Compact Environment Anomaly Sensor (CEASE), a small, lightweight, low-power sensor to provide satellite operators with alerts of space particle hazards to their satellites
- The Solar Mass Ejection Imager (SMEI) will detect and track coronal mass ejections (CMEs) all the way from the sun to Earth.

Selected project detail is tabulated in “Projected Applications,” below.

Enabling Technologies *(Unconstrained)*

- Autonomous, adaptive, self-training algorithms for tasking, mission planning/ management, processing, exploitation, and dissemination
  - Real-time resource planning
- Improved sensors with 3D coverage, timely refresh rates, and improved accuracy
  - Acquisition, pointing and tracking,
- Increased sensor range and sensitivity technologies
  - Atmospheric, radiant and celestial background characterization, databases, modeling, and processing
- Advanced electro-optical (EO) technology (e.g., for long-dwell sensing)
- Hyperspectral sensing: improved low power, high capacity on-board processors
- Hyper- to ultra-spectral imagery (HSI USI) sensors (100s to 1000s of bands)
  - Exploitation of multiple-band IR sensor data
- Exploitation of evolving HSI/USI approaches
  - E.g., improved HSI/USI collection via focal plane arrays (FPAs)
- Visible and multispectral/hyperspectral and very short wavelength infrared (VSWIR) sensors/ imagers
  - Multi- to ultra-spectral detector materials, processes, and manufacturing
- Large FPA detector materials science and manufacturing
- Advanced small, high-capacity, space-qualified cryocoolers;
  - More efficient on-orbit storage of cryogenic hydrogen
  - More efficient infrared applications
  - Advanced regenerator/phase-change materials
- Space-based laser/lidar remote optical sensing
- Sensors to monitor the space environment and alert host spacecraft of natural hazards, man-made threats or anomalies
- Multi-point space weather measurements
- Real-time remote-sensing technologies to study ionospheric effects
  - E.g., scintillation of RF signals
- Advanced spatial resolution techniques
- Hyper resolution techniques
- Basic research leading to development/improvement of advanced sensor technologies and weather prediction models
- Advanced computing:
  - Hyper-performance hardware to run advanced, high-resolution models at to provide real-time data
  - Improved algorithms for speed, accuracy, and efficiency
- Reprogrammable radios and other electronics system components
- More efficient solar cells, batteries (chemically or thermally generated electricity, such as thermionic power generation and thermo-electric conversion)
  - E.g., lithium ion/polymer hybrid batteries
  - Affordable solar cell materials and manufacturing
- Radiation hardening and shielding of components
  - Radiation-resistant composites and associated materials
  - High-temperature and radiation-resistant electronic materials
  - Flash radiation-hardened digital memory (e.g., SiC)
- Isothermality technologies
- Advanced filters and limiters for satellite survivability
- Advanced effects phenomenology

Projected Applications

A wide range of applications exists; the following is a selection.

Category	Project	Status	Agencies
Enhanced Atmospheric Characterization	• ***WindSat*** – Measure ocean surface wind speed and direction – Provides risk reduction for NPOESS/CMIS	Experiment	Navy
	• ***Communication/Navigation Outage Forecasting System (C/NOFS)*** – Equatorially orbiting satellite to warn of potential outages to GPS navigation and satellite comm links due to hazardous space environmental conditions	ACTD	Air Force
	• Additional projects with sensors hosted on both operational and experimental spacecraft to measure and characterize the upper atmosphere	Development	Air Force Navy
Enhanced Oceanic Characterization	• ***Geodetic/Geophysical Satellite (GEOSAT) Follow-On (GFO) satellite*** – Enhancements to ocean wave height and topographic measurements	Pre-operational calibration/ validation	Navy
	• ***Radar Altimetry*** – Characterization of oceanographic thermohaline and geostrophic surface current structure	Development	Navy
	• Additional projects to characterize ocean surface	Development	Navy
Improved Space Characterization	• ***Compact Environmental Anomaly Sensor II (CEASE II)*** – To demonstrate a small, low-power instrument resident on a host spacecraft to reduce anomaly resolution time and increase situational awareness	ACTD	Air Force, Navy
	• ***Advanced Solar Telescope (AST)*** – For solar disturbance monitoring	Proposed project	Nat'l Science Foundation
	• ***Solar Mass Ejection Imager (SMEI) and space-based coronographs*** – Advance warning of coronal mass ejections (CMEs) and track their propagation from the Sun to Earth	Experiment development	Air Force
Advanced Environmental Monitoring Systems	• ***National Polar-orbiting Operational Environmental Satellite System (NPOESS)*** – Passive microwave instruments will provide global oceanic and atmospheric data of direct operational relevance. Multiple primary sensors are planned	Engineering development	DOC-DoD-NASA
	• ***Small satellite concepts*** – To provide sensors for global environmental data and space weather sensing – Data acquisition using STRV-2c/d	Concepts	DARPA, Air Force BMDO
	• ***Naval EarthMap Observer (NEMO)*** – To collect broad-area HSI for Naval and Civil users	Prototype development	Navy, DARPA, Industry
	• ***Indian Ocean METOC Imager (IOMI)*** – To demonstrate hyperspectral atmospheric characterization from GEO, using on-board high-performance processing and data compression	Development	Navy, NASA, NOAA

Category	Project	Status	Agencies
Enhanced METOC Forecasting Models	• Projects to update the weather database, help exploit measurements, and develop predictive models • Projects to improve forecasting for the atmospheric, ionospheric and magnetospheric environments	Research Research	Air Force, Navy Air Force, Navy
Military-Civil Cooperative Activities	• Prediction of forest fires • Pacific Disaster Center functions • Early detection of volcanic activity, both to mitigate effects and to support disaster relief	Research On-going Research	(Several) Fed agencies (Several)

Opportunities for Partnering

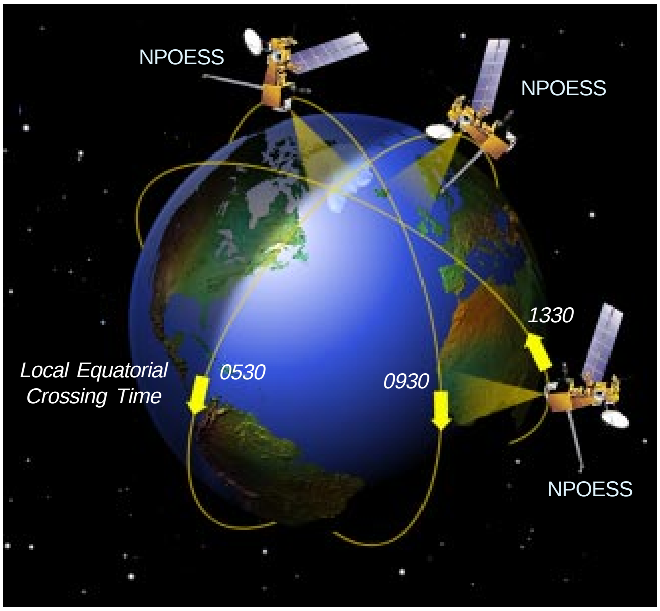
Partnerships and cooperative programs exist within the DoD and with other agencies. For example, NOAA, the Navy and Air Force cooperate on DMSP; the Joint Typhoon Warning Center also includes a broad range of military-civilian coordination. The Navy and NOAA continue to identify new areas for cooperation, such as operational numerical modeling, data exchange, risk-reduction efforts, and mutual backup among several agencies. Federal and commercial agencies use each other's R&D and missions of opportunity to obtain space environmental data.

External partnerships also include the DOC-DoD-NASA collaboration on NPOESS, which allows significant opportunities to transition Air Force and Naval space technologies and models into operations. NPOESS's six primary sensors will cover wide electromagnetic and operational applications ranges to meet evolving military needs. Meanwhile, the Navy's Windsat will provide risk reduction for the NPOESS Conical Microwave Imager Sounder (CMIS), a DMSP microwave suite follow-on that will use passive microwave radiometry.

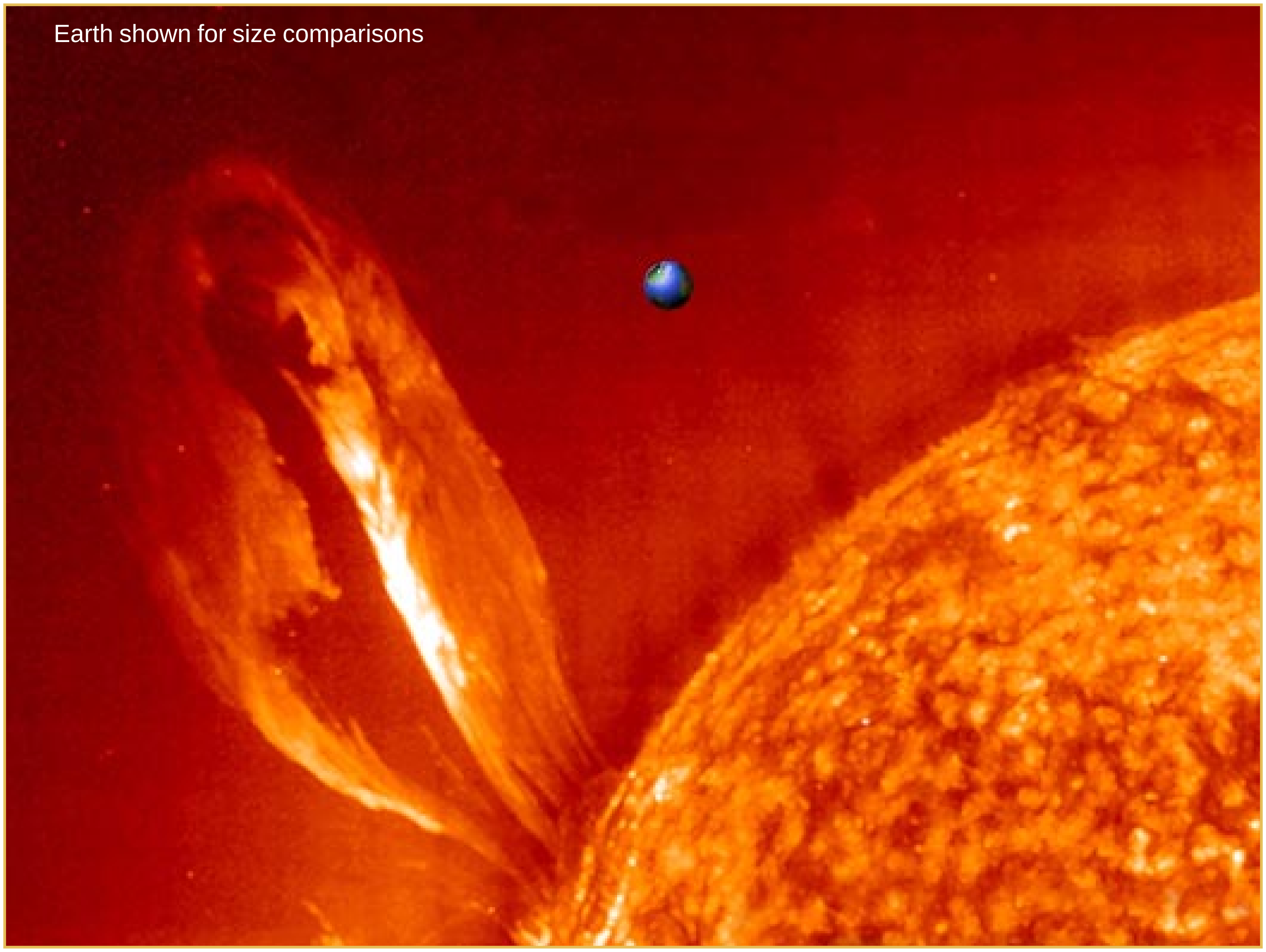
The Navy is partnering with NASA to combine its IOMI program with NASA's Geostationary Imaging Fourier Transform Spectrometer (GIFTS) program to demonstrate hyperspectral atmospheric characterization from geosynchronous orbit. The IOMI/GIFTS project will demonstrate critical sensor technologies for future civil and military weather systems, with the potential to greatly improve global weather forecasting. The project will include direct data downlink to the fleet and data distribution to the Navy Fleet Numerical Meteorological Oceanographic Center, NOAA, NASA, and the world meteorological community.

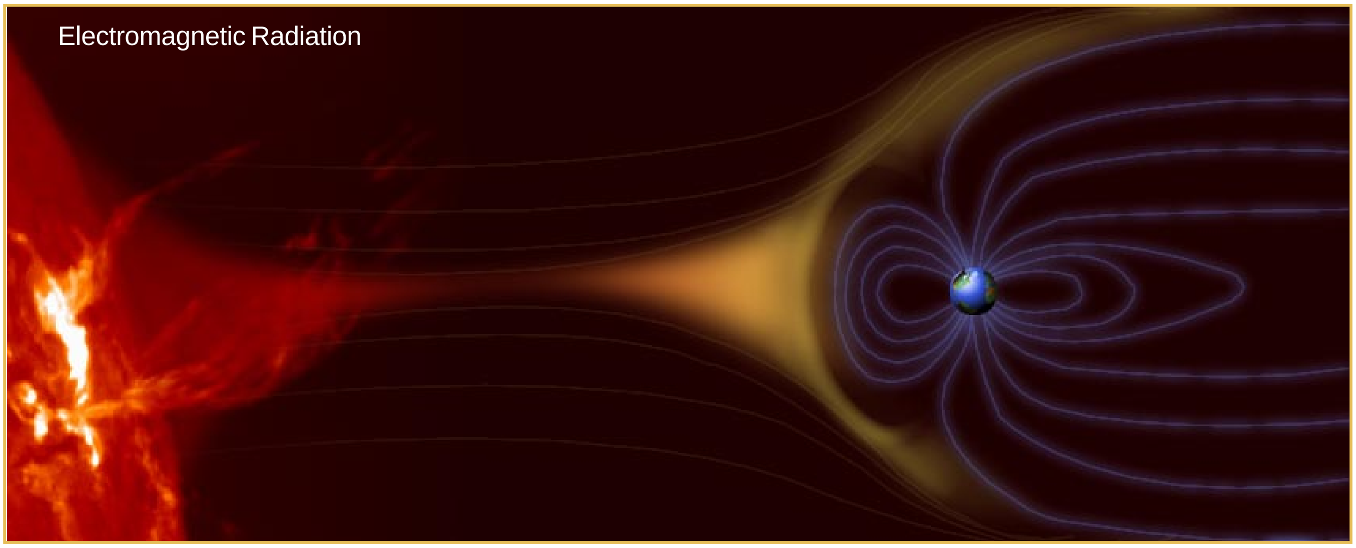
BMDO is cooperating with the Air Force, NASA, the UK and the European Space Agency (ESA) over measurement of Van Allen Belt fluctuations and the testing of radiation resistance of key electronic components. BMDO and NASA/JPL are measuring the micrometeoroid and debris environment in low- to mid-altitude orbits.

Further, unclassified Service-produced data is made available to NOAA for public distribution. Service partnerships with the NSF, NOAA and NASA currently exist in the National Space Weather Program. Finally, new NASA and Navy initiatives in space weather and space S&T research will allow the DoD to test new space sensing technologies and participate in continuous solar and Earth environmental monitoring.



National Polar-orbiting Operational Environmental Satellite System (NPOESS) Constellation





Space Weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. **Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids,** leading to a variety of socio-economic losses.

National Space Weather Program
Strategic Plan, August 1995

10. Space Control

Area Description

Space control is defined as:

> Combat and combat support operations to ensure freedom of action in space for the United States and its allies and, when directed, deny an adversary freedom of action in space. *

Space control itself is dependent on assured access, consisting of space launch and satellite operations and now considered part of the space support mission area by the operational community. Space support provides communication to, through and from space.

Space control includes a mix of defensive and offensive measures to achieve its objectives. Capabilities required to accomplish the mission fall within key interrelated tasks of surveillance, protection, prevention, and negation.

Space control requires a systematic approach:

- Initially, our ability to sustain the capabilities considered essential to support single-Service, joint and combined operations across the spectrum of conflict depends on our ability to protect existing ground and on-orbit space assets and their associated data links.
- Second, enhanced protection for future space systems is fundamental to ensure that continuity of space products and services to friendly forces is maintained and improved.
- Third, these assets must be capable of surveying their own space environment, both for self-protection against natural and man-made threats and to determine if they are under attack.
- Should hostile use of friendly systems' products or services be attempted, or an attack be mounted against them, the next step would be to defend against such exploitation or assault.
- Finally, the ability to negate hostile activity may be necessary. Clearly these space control tasks will depend on national policy decisions; meanwhile, their enabling technologies must be defined and pursued to assure timely acquisition of required capabilities;

The space control mission/technology area requires a phased approach to achieve its goals, to include:

- Interim improvements to surface-based and airborne assets while the long-term migration of the space surveillance mission to space-based assets takes place. This migration would involve both collateral use of systems primarily supporting other missions (such as the Space-Based Infrared System [SBIRS]) and, eventually, more dedicated systems to assure options for control of the ultimate "high ground" of space.
- Determination of the best operational role for optical space surveillance assets.
- Active imaging technology programs and their testbeds to investigate the full range of target performance and scalability issues that will follow initial test results.
- An evaluation and selection process for system options for defensive and potential offensive operations, followed by a process to transition technology development activities to system acquisition programs.


Space Tracking


Ground Stations

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* Department of Defense Directive 3100.10, July 1999.

Mission Area Objectives

<table>
<tr><th>Space Surveillance</th><th>Protection</th><th>Prevention</th><th>Negation</th></tr>
<tr><td>• Precise detection, tracking and identification of space objects of interest
• Ability to characterize objects as threats or non-threats
• Detection and assessment when a threat payload performs a maneuver or separates</td><td>• Detection and reporting of space system malfunctions
• Characterization of an attack and location of its source
• Withstanding and defense against threats or attacks
• Restoration of mission capability</td><td>• Prevent adversarial use of U.S., allied or third-party capabilities</td><td>• Precision negation of adversarial use of space
• Strike assessment or BDA against target sets</td></tr>
<tr><td colspan="4">Supporting Capabilities
Ground- and space-based high-resolution imaging
RF and optical space-based sensor systems
Fusion and registration of data from heterogeneous sensors
Netted, encrypted laser communication links
Automatic cross-cueing
On-orbit maneuvering, servicing, and maintenance
On orbit diagnostics, processing, and mission management
On-board detection of space environment hazards
Advanced laser detection and protection systems
Fusion and dissemination of hazard- and threat-related information
Space-based detection and location of surface and airborne RF jamming
Capabilities to neutralize threats
Techniques for interference or "soft kill"
Home-on-jam (HOJ) weapons
Ground- and space-based high-power lasers</td></tr>
</table>

Current Technology Initiatives *(Highlights of Current FYDP)*

Current projects address space surveillance, protection, prevention and negation tasks. As a basis:

- An optics-upgraded Maui Space Surveillance Site (MSSS) telescope will produce high-resolution images for the Space Surveillance Network (SSN) in FY01. Further upgrades will include post-processing algorithms to improve image quality, additional sensors to provide multi-wavelength capabilities, and potentially a laser guidestar capability to improve performance against dim targets
- Also in FY01, the Intelligence Data Analysis for Satellite Systems (IDASS) workstation will provide improved processing and analysis of optical imagery to identify space objects and assess mission payloads
- Integration of a ladar to the MSSS telescope will provide a 30-db signal-to-noise gain for space object engagements, followed by evaluation for range-Doppler imaging and space debris tracking applications. The system may also be used as a contributing sensor to the SSN
- The Geo Light Imaging National Testbed (GLINT) program will demonstrate a satellite active imaging capability out to geosynchronous altitudes

Protection/prevention capabilities will be sought via:

- Satellite threat warning/attack reporting technology development and space-based demonstrations for both the Miniature Satellite Threat Reporting System (MSTRS) and the Advanced Laser Sensor Development (ALSD). Further development of protection technologies will emphasize laser/electro-optic protection materials, with a space demonstration planned for the FY04-05 time period

We will continue additional defensive and offensive concept analysis and advanced technology development to support a Space-Based Laser (SBL) for the FY12-13 time frame both to perform space surveillance and to neutralize ballistic missile targets.

Selected additional project detail is tabulated in "Projected Applications," below.

Enabling Technologies *(Unconstrained)*

- Autonomous, adaptive, self-training, real-time resource planning algorithms for tasking, mission planning/management, processing, exploitation, and dissemination
- Automated cross-cueing, dynamic database fusion, synergy of imagery, spectral and signal processing functions, phenomena and information technologies
- Artificial Intelligence (AI) for data fusion
- Neural networks
- Automatic control, fuzzy logic
- Increased satellite on-board data processing and storage for timely data delivery
  - Non-volatile random access memory
- On-orbit maneuvering, diagnostics, processing and mission management technologies
- Fusion processing software algorithms
- Miniaturized, scalable, power-efficient electronic components and mechanisms
  - E.g., fiber optics, optoelectronics, photonics, microelectromechanical systems (MEMS)
  - E.g., superconducting electronics to eliminate need for sensor cryocooling
- Large, lightweight support structures and materials
- Shape memory techniques and alloy materials
- Active and passive electromagnetic spectrum devices to direct, disseminate, focus and transmit — as well as to detect, extract, sense and receive — energy:
  - Heat (infrared [IR])
  - Visible light
  - Radio frequency (RF)
- Ground-based high-resolution optical/radar/multi-spectral imaging technologies (active or passive)
- Increased sensor range and sensitivity technologies
  - Atmospheric and radiant background characterization, modeling, and processing
  - Improved atmospheric compensation and target classification algorithms for multi-spectral/hyperspectral image processing
- Multiple RF and optical sensors, processors, links, and host spacecraft integration technologies
- Exploitation technologies for bistatic phenomenology of targets and clutter characteristics
  - Bistatic space-time adaptive processing algorithm validation
- Multistatic time and frequency correlation, signal processing, and data fusion
- Advanced target detection technologies
  - E.g., acousto-optical detection and spectral signature exploitation (to see through clouds)
- Non-intrusive inspection technology
- Advanced electro-optical (EO) technology
- Hyperspectral sensing: improved low-power high-capacity on-board processors
- Hyper- to ultra-spectral imagery (HSI-USI) sensors (100s to 1000s of bands)
- Advanced IR technologies

  - Quantum cascade and interband semiconductor IR laser sources
- Multispectral/hyperspectral and very short wavelength infrared (VSWIR) sensors/imagers
  - Multi- to ultra-spectral detector materials, processes, and manufacturing
- Large focal plane array (FPA) detector materials science and manufacturing
  - E.g., staring FPAs for multispectral detection, read-out integrated circuits (ROICs), quantum well IR photodetectors (QWIPs)
- Advanced small, high-capacity, space-qualified cryocoolers
  - More efficient on-orbit storage of cryogenic hydrogen
  - More efficient infrared applications
  - Advanced regenerator/phase-change materials
- Low/high-power laser atmospheric compensation and beam control
  - Optical phase conjugation
  - Adaptive laser optics
  - On-orbit dimensional control
  - Jitter and vibration management
- Advanced acquisition, pointing and tracking techniques
- Space-based high-resolution optical/radar/multispectral imaging technologies (active or passive)
- High-energy laser technologies for:
  - Ground-based high-power laser
  - Space-based high-power laser
- Space-based mirrors for high-power laser relay
  - Large-aperture, lightweight, modular, deployable membrane mirrors/optics, and support structure materials
- Durable thin-film substrate/membrane/coating materials, processing, and manufacturing
- Nonlinear optical materials for specialized sensors
- Optically efficient and variable-emittance mirror coatings
- On-orbit servicing of mirror coatings
- Advanced RF technology
  - Photonics for phase-shifting and beam-forming
  - Spectral analyzers and algorithms
  - Digital RF memory (DRFM)
- Advanced HOJ technology
- Advanced synthetic aperture radar (SAR)
- Advanced automatic target recognition (ATR), moving target indication (MTI), and orbital dynamics processing algorithms
- Large affordable, lightweight RF reflectors and antenna designs
  - E.g., inflatables, deployable array-fed reflectors
  - E.g., solid state phased array electronically steerable antennas
  - Higher strength-to-weight and composite materials and designs
- Radar components with higher frequency and power output
  - High-temperature semiconductor materials for RF/radar components
- Advanced, lower-cost, higher-frequency/bandwidth transmit/receive (T/R) components
- Improved front-end noise rejection for RF systems
- Advanced mixers and analog-to-digital (A/D) converters
- Advanced signal excision techniques
- Laser/optical communications and associated acquisition/tracking/pointing for space-space, space-air, and space-ground applications
- Non-volatile memory optical computing/communications
- Advanced laser and microwave communications technologies for space-space, space-air, space-ground links
  - Advanced netting and encryption technologies
- Reprogrammable radios and other electronics system components
  - Field programmable gate array (FPGA) technologies

- Autonomous, longer-life, higher-energy/power-to-weight on-orbit power generation, conditioning, distribution, and storage
- More efficient solar cells, batteries (chemically or thermally generated electricity, such as thermionic power generation and thermoelectric conversion)
  - E.g., lithium ion/polymer hybrid batteries
  - Affordable solar cell materials and manufacturing
- Integrated/active thermal control
  - Electronics cooling
- Radiation hardening and shielding of components
  - Radiation-resistant composites and associated materials
  - High-temperature and radiation-resistant electronic materials
  - Flash radiation-hardened digital memory (e.g., SiC)
- On-board detection and technologies for space environment hazards
  - Advanced laser detection and protection technologies
  - Detection and location of surface and airborne RF jamming
- Satellite laser and RF interference/vulnerability mitigation
  - Bi-/multistatic techniques
  - Synthetic/virtual apertures
- Advanced filters and limiters for satellite survivability against directed-energy weapon (DEW) threats
  - Laser-hardened materials and concepts for sensors
- Isothermality technologies
- High heat-dissipating thermal doubler/plane materials
- Advanced effects phenomenology
  - Techniques for interference or “soft kill”
- Human-system interfaces for information exploitation and decision-making
- Control center technologies
  - Write once read many (WORM) storage
  - Archival mass storage
- Advanced team training technologies.

Projected Applications

Activities	Status	Agencies
Space Surveillance (ground-based)		
• ***Full-Scale Adaptive Optics***	Technology insertion	Air Force
– Integration with Maui Space Surveillance Site's (MSSS's) 3.7m telescope		
• ***Hi-Class Ladar***	Technology development	Air Force
– Integration with Maui's 3.7m telescope; 30-db gain for space object engagements		
– Space surveillance capability; range-doppler imaging and space debris tracking options		
• ***Imagery exploitation tool***	Technology development	Air Force
– Intelligence Data Analysis for Satellite Systems (IDASS), ground-based software to enhance the processing and analysis of Maui's high-resolution imaging products		
• ***Active Imaging Testbed experiments***	Technology experiments	Air Force
– Active imaging evaluation (of experiments completed in FY00)		
– Results transitioned to Geo Light Imaging National Testbed (GLINT) to demonstrate optical imaging of GEO space objects		
– Later GLINT upgrade to provide residual operational capability		
Space Environmental and Threat Reporting		
• ***Compact Environmental Anomaly Sensor II (CEASE II)***	ACTD	Air Force
– To monitor harmful elements of the space environment and provide real-time alerts to the host spacecraft		
• ***Space Threat Warning and Reporting (STW/AR)***	Technology demonstrations	Air Force
– To support defensive counterspace capabilities		
– ***Miniature Satellite Threat Reporting System (MSTRS)***		
— To support the RF portion of STW/AR		
– ***Advanced Laser Sensor Development (ALSD)***		
— To support the laser portion of STW/AR		
Space-Based Laser Integrated Flight Experiment (SBL IFX)	Technology program	Air Force BMDO
– On-orbit demonstration of integrated performance (planned for FY10-12 time frame)		
– Parallel programs to enable development of an operational SBL		
– Concept refinements via the SBL Affordability and Architecture Study		
– Continuing space optics and laser technology studies		
Space Maneuver Vehicle	System concept	Air Force
– Maneuverable satellite bus with interchangeable payload capability		
– Launchable on demand, maneuverable to desired locations		
– Able to rendezvous and co-orbit with LEO/MEO satellites, fly by GEO satellites		
– Would be able to carry or dispense any type of payload		

ACTD Advanced Concept Technology Demonstration

Opportunities for Partnering

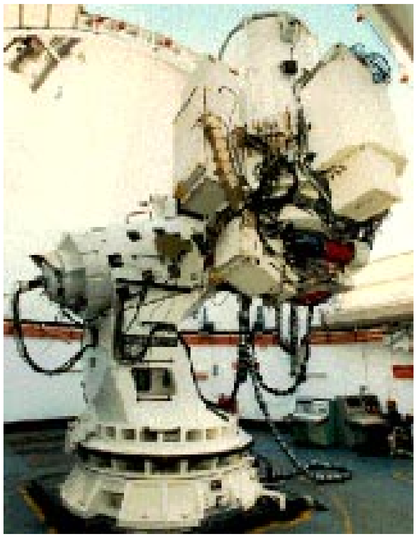
The DoD is pursuing partnerships in space control activities among the Armed Services, Defense Agencies, and interagency national security organizations, as well as work with commercial and foreign entities. Commercial systems and technologies are being leveraged and exploited where feasible. Current examples include:

- The Air Force-BMDO SBL IFX, which will demonstrate on-orbit operation and lethality of a high-energy laser system against a missile in boost phase
- Air Force-NSF use of the Maui Space Surveillance Site's new 3.7-meter telescope and associated adaptive optics system for astronomy, which will combine operational and scientific work
- Air Force plans to partner with BMDO, NASA and NOAA for its multi-link lasercom development initiatives.

Maui Space Surveillance Site (MSSS)

The 3.7m telescope's dome and facility

The 3.7m Advanced Electro-Optical System Telescope



The 1.6m Telescope

11. Force Application

Area Description

For the most part, the space aspects of Force Application are currently limited to ballistic missiles, which fly through space on sub-orbital trajectories, and to operational use of the C3 services and ISR products of space-based sensors and links. As we look to the future, space-based systems and space force mission options, such as active missile defense (BMD) may become increasingly important. Meanwhile, it is being recognized that space-based forces would add capabilities for deterrence and flexible response when time is absolutely critical, when risks associated with other options are too high, or when no other course of action is practical. At the same time, deployment of such systems is significantly limited by international treaties and U.S. national policy.

From a technology perspective, the sustainment of our intercontinental and sea-launched ballistic missile (ICBM, SLBM) assets is closely tied to the continuing development of solid rocket motor technologies for the Space Transportation mission. Ballistic missile technologies that are readily applied to other space missions include advanced propulsion techniques, solid state electronics (especially for guidance and navigation), advanced antennas, anti-jam GPS, plasma physics, high-temperature materials, reentry vehicle leading edges, thermal protection systems, sensor systems, smart fuze packages, desensitized ordnance, and high-speed projectiles.

Defensive force application via space comprises a family of theater and tactical missile defense (TMD) systems, directed energy systems, and the option for national missile defense (NMD). All are in various stages of definition or development, and all rely on space products and services for their effective operation.

As for offensive force application, the precision of conventional weapon strike is being enhanced by improvements in the accuracy and timeliness of targeting information to cruise missiles and strike aircraft from space-based assets. The concept labeled “sensor-to-shooter” captures the essence of providing specifically required C4ISR information directly to a weapons (or other operational) platform in time to ensure mission success. While the engagement parameters may vary (e.g., for ordnance aimed at a fleeting target or a BMD intercept), a high degree of automation and link reliability is essential. Space-based systems, by their ubiquity and sensor capabilities, already play a key role in bringing this concept to maturity as the “cutting edge” of future force application.

Relevant space products (for strategic or tactical uses) include high-resolution imagery, ground MTI (GMTI) maps, and Digital Terrain Elevation Data (DTED). DTED and imagery can be used before hostilities to plan U.S. strike strategies and missions. Timely GMTI and SAR imagery can be integrated with strike aircraft targeting systems to provide battlefield dominance in a dynamic environment. Precise DTED of target areas can be uploaded to cruise missiles and correlated with an on-board altimeter for highly accurate all-weather midcourse and terminal guidance, which is autonomous and thereby resistant to both GPS jamming and covert techniques. After a strike, rapid battle damage assessment/information (BDA/BDI) can enable dynamic air tasking order updates, thus greatly compressing engagement and reengagement timelines.

Maturation of space-based radar capabilities is key to enabling rapid all-weather, day/night strike operations worldwide, from locating targets (GMTI/SAR), guiding weapons (DTED), to BDA (SAR). Additional focus is also needed on:

- Core structures, electronics, and propulsion
- Enabling technologies for space delivery of conventional systems, to include on-orbit support
- Development of relay mirrors to use with high-power laser sources, which could enable a ground-based laser (GBL) source or a longer-term space-based laser (SBL) capability for force application missions.

Mission Area Objectives

Deterrence	• Capable and reliable ICBM and SLBM forces • Ballistic missile command, control, and communications (BMC3) • Deter/counter weapons of mass destruction (WMD)	
Defensive	• Support development of NMD forces and NMD C3 • Development of non-ballistic missile defensive concepts, to include: – Ground- and space-based directed energy and kinetic energy options • Protection for friendly missile capabilities • Provision of the following capabilities for defensive forces: – Availability on demand – Full-spectrum engagement – Real-time combat assessment	
Offensive **(Concept Planning and/or Technology Demonstration Only)**	• Space-Based Laser (SBL) • Other space-leveraged offensive concepts • Neutralization of: – Adversaries' air defenses – Adversaries' air and cruise missile capabilities – Non-WMD surface targets • Concepts for on-orbit storage and resupply of consumables, such as thrusters, fuels, and power sources	• *All offensive forces:* – *Available on demand* – *Flexibly employable* – *Flexible effects* – *Real-time combat assessment* – *Worldwide coverage*
Supporting Capabilities	Improved space detection/identification of critical moving, hidden or subsurface targets Exploitation of ISR products to enable target acquisition and characterization Very high capacity on-board computing Space-based high-power directed energy (SBL) On-orbit support, storage, and replenishment Improved robustness and sustained effectiveness throughout reentry Ground-based high-power directed energy with on-orbit mirror relays	

Current Technology Initiatives *(Highlights of Current FYDP)*

Funded basic research applicable to force application functions includes advanced materials, electromagnetics, nanotechnologies, propellants and propulsion technologies, electronics, high-performance computing, energy storage concepts, robust communication networks, software and knowledge-based systems, image processing, advanced solid state and electro-optical sensors, hyperspectral imagery, information fusion and visualization. At a more mature level, solid rocket motor technologies from ICBM/SLBM sustainment activities that are being leveraged include:

- High-temperature materials
- Thermal management
- Plasma physics
- Solid propellants.

In addition, research continues into turbulence, drag, and neutral density variations in LEO, and into artificial intelligence, ground-based space surveillance, hypersonics, aerospace structures, and plasma physics applicable to transatmospheric space vehicle design. Directed energy is being explored at optical and microwave wavelengths, and other research is focusing on impact and penetration concepts relevant to space debris and micrometeoroid threats.

The SBL Integrated Flight Experiment (IFX) program is currently funded to complete an on-orbit demonstration of integrated performance and lethality against ballistic missile targets in the FY12-13 time frame. Its four major technology areas for the near term are:

- Laser technologies
- Beam control
- Beam direction
- Acquisition pointing and tracking.

Selected additional project detail is tabulated in "Projected Applications," below.

Enabling Technologies *(Unconstrained)*

- Autonomous, adaptive, self-training, real-time resource planning algorithms for tasking, mission planning/ management, target ID/ tracking and battlefield learning, and data processing, exploitation, and dissemination
- Improved precision time sources (10-ps timing accuracy) (atomic/laser clocks)
  - Network-centric communication synchronization techniques
- Dynamic target databases with improved data fusion and timely information delivery
- Very high capacity on-board computing and data storage
- Advanced "sensor-to-shooter" technologies to enable target neutralization and real-time assessment
- Human-system interfaces for information exploitation and decision-making
- Advanced ISR technologies to enable target acquisition and characterization
- Improved detection/ID of critical moving targets, both ground and air
- Improved characterization of hardened and deeply buried targets
- Increased sensor range and sensitivity technologies
  - Atmospheric and radiant background characterization, modeling, and processing
  - Improved atmospheric compensation and target classification algorithms for multi-spectral/hyperspectral image processing
- Advanced small, high-capacity, space-qualified cryocoolers
- Low/high-power laser atmospheric compensation and beam control technologies
- Advanced acquisition, pointing and tracking techniques
- High-energy laser technologies for ground/ space-based high-power lasers
- Space-based mirror technologies for high-power laser relay
- On-orbit laser servicing and replenishment of consumables
- Kinetic energy technologies
- Ballistic missile sustainment technologies to assure continued functionality of structure, propulsion, guidance, fuzing and payload subsystems
- Advanced weapon modeling and simulation (M&S) and test technologies
  - Non-destructive evaluation (NDE) technologies for prediction of rocket motor service life
- Advanced temperature/erosion/vibration-tolerant materials and technologies to assure missile/spacecraft reentry:
  - Advanced materials for solid rocket motors and reentry vehicle leading edges
  - Plasma effects technology to minimize signal blackout
  - Improved window/antenna materials for reentry systems.

Projected Applications

Solid Rocket Technologies

- Advanced and enhanced solid rocket motor technologies
- Advanced reentry vehicles
- Integrated geolocating guidance systems

Advanced AMTI/GMTI for Battlefield Strike Operations

- Applications of space sensor imagery to offensive targeting

On-Orbit Support

- Reusable Launch Vehicles (e.g., SOV)
- On-orbit servicing (e.g., SMV)

Robust, tightly coupled GPS/INS systems for use with launch systems

Next-generation solid rocket technologies:
– Lower-size/weight/cost GPS/INS systems –
– Low-cost propellants, cases, liners, nozzles –

Advanced precision navigation instruments, nose cones, leading edges, thermal protection systems, smart fuze packages, and high-speed projectiles

Maturation of:
– Space Web template updates –
– SBL and Full Power Relay Mirror System –
– Mobile GPS/INS-based range tracking and command destruct system –
– Advanced precision strike vehicle designs –
– GPS reacquisition after reentry plasma blackout –
– The strategic-grade Multi-Mission GPS/INS system –

Utility assessment of space sensor imagery, GMTI and DTED for battlefield strike operations

Resupply of space-based assets

Storage of consumables

Leverage of Solid Rocket Technologies for Space Transportation

- Solid rocket technologies
- Low-cost/hazard propellants
- Post-boost control systems

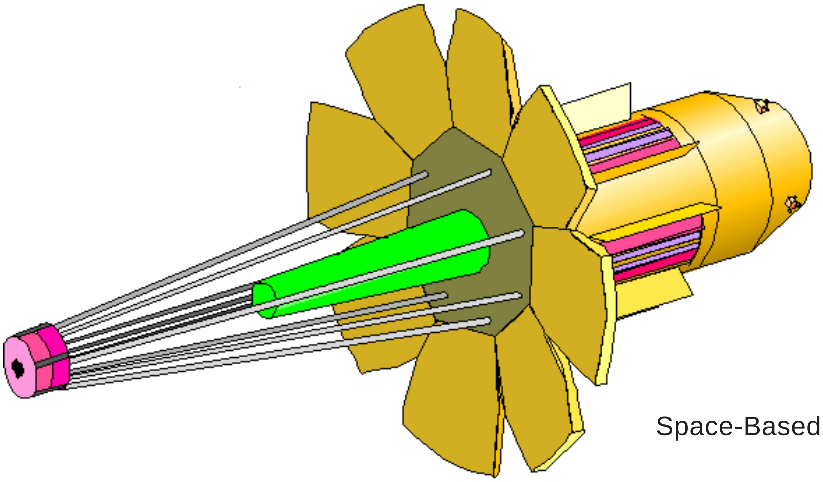
Potential Offensive/Defensive Systems

- SBL demonstration
- Full-Power Mirror Relay System
- Precision targeting support
- KE systems

Opportunities for Partnering

The Air Force and Navy jointly fund Draper Laboratories' development of the Multi-Mission Inertial Navigation System (MMINS) for missile life extension and future replacement. Ohio University provides expertise to the Air Force for public safety certification of GPS/INS range instrumentation.

The Air Force and BMDO are jointly funding the SBL Integrated Flight Experiment (IFX) program, which will lead to on-orbit tests of a high-power laser system to demonstrate integrated operation, performance and lethality against a TBM target. This demonstration program could be extended to encompass force application missions.



Space-Based High Energy Laser System

12. Microsatellite Technology

Definitions

The term "microsatellite," or "microsat" for short, has become a generic reference for entire new classes of satellite whose size and weight reduction from traditional satellites may be measured in orders of magnitude. Their specific nomenclature derives from their mass, as follows:	• Traditional satellites weigh upwards of 1,000 kg, and require medium or large launch vehicles to boost them into orbit • Smallsats weigh on the order of 500 kg, and are defined as fitting on the smallest class of launch vehicles • Microsats generally range from 100 down to 10 kg • Nanosats range from 10 down to 1 kg • Picosats weigh less than 1 kg.

Effects of Miniaturization

Miniaturization techniques have already been used for years to reduce spacecraft component size and weight, and also costs. Many spacecraft components lend themselves to smallness and even to miniaturization, such as:

- Optical cameras and reaction wheels for certain applications, primarily as a result of investments by the Strategic Defense Initiative Organization/ Ballistic Missile Defense Organization (SDIO/ BMDO) during the past ten years
- Data processing systems, which have become more capable per unit size and weight. Because of this, several spacecraft susbsytem computational functions are now integrated into one computer, which translates into size reductions across the total spacecraft.

While "smaller" generally equates to "lighter," one area has seen size reduction overtaken by even greater proportional weight reduction. This has resulted from the increasing use of composites, especially for large spacecraft structures such as antenna and solar cell panels and the satellite body itself. Further, as less fuel needs to be carried for on-orbit maintenance of the lighter spacecraft, its reaction control systems can also be made smaller, with the secondary effect that its size and weight can be further reduced.

While these are important gains, they typically constitute a few or at most a few tens of percentage-point reductions from one spacecraft generation to the next, rather than orders-of-magnitude reductions. Also, these size and weight reductions have occurred because of significant technology investments over the past 20 years. For example, if one examines a specific operational mission with a constant performance requirement, a follow-on satellite may experience up to a 50- to 66-percent weight reduction over a 15-year generation. An equivalent period and level of investment will likely be required to explore the promise of new capabilities and concepts projected for microsatellite classes of spacecraft.

The laws of physics present obstacles to significant size/weight reductions in some important areas, such as aperture requirements for useful reception or transmission of electromagnetic radiation. For example, sparse or distributed apertures provide substantially improved resolution without increasing weight. However, sparseness cannot improve signal-to-noise ratio or gain, which are the limiting parameters for most surveillance and communications systems. In addition, if multiple (smaller) satellites are used for distributed aperture systems, additional instersatellite communications requirements (along with their associated antenna and pointing subsystems, additional data processing needs, and increased energy requirements) diminish the size and weight gains achieved by the system overall. Typically, operational systems require significant energy for useful data processing, communications, and now propulsion. Even with efficiencies, solar cells and apertures sufficient to gather solar energy will remain large. Thus, gains to date have been evolutionary, vice revolutionary.

At this stage, the major benefits of miniaturization include:

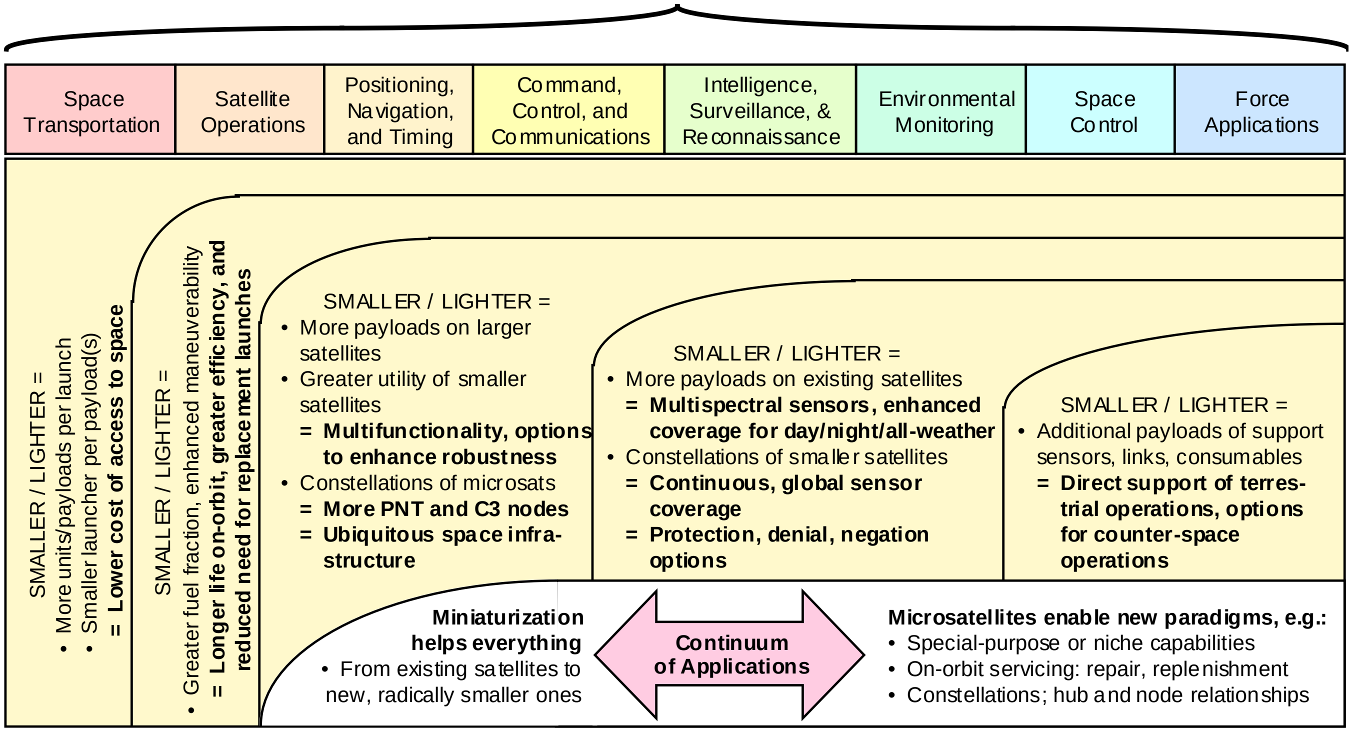
- Reduced component and total spacecraft costs of manufacture, attributable to design innovations, increased use of composite materials and microelectronics, manufacturing efficiencies, and economies of scale
- Significantly reduced costs to orbit, either by fitting smaller, lighter satellites on smaller launchers or by enabling a given launcher to carry more such spacecraft to orbit
- In many (but not all) cases, enabling the same or analogous mission performance by smaller but more numerous space platforms. This may involve smaller satellites replacing or augmenting satellites already on orbit, or such smaller satellites held in reserve for quick-response contingency launch
- The emerging potential of microsatellite classes to perform new or specialized missions, or to perform some of the same missions better, by virtue of additional numbers and interactive fleet capabilities.

So far, most of the miniaturization benefits achieved have been for existing satellites, but, as current technology miniaturization trends continue, it has become popular to predict the operational deployment of microsats, nanosats, and even picosats. For the future, the utility of microsats *per se* and the new operational concepts they may enable will depend on a series of technology experiments to progressively establish their feasibility and utility. A summary assessment of such factors is depicted below.

More specifically and over the longer term, microsats of appropriate mass, size and capability are being considered to:

- Augment existing constellations during contingency or theater operations
- Perform special-purpose or limited-scope "niche" missions, such as nuclear detonation (NUDET) detection
- Operate as distributed or multifunctional platforms in the performance of several space missions
- Support Space Control concepts by providing additional platforms for Defensive or Offensive Counterspace options
- In conjunction with the foregoing, provide unique capabilities to enable new, innovative operational concepts, such as:

Miniaturization Effects Across the STG Mission Spectrum

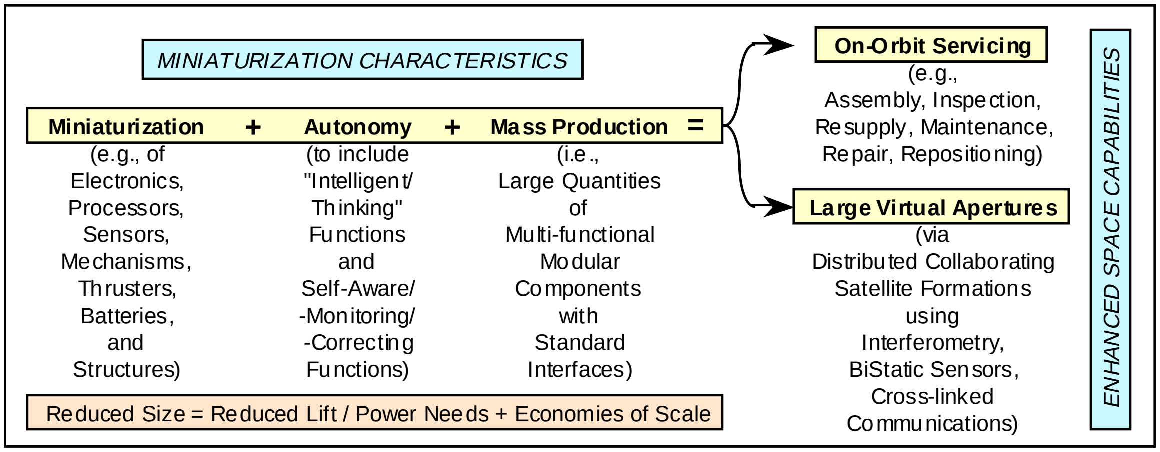


  - On-orbit maintenance, supply and servicing of operational satellites
  - The use of satellite clusters to provide virtual apertures for sensing operations
  - Distributed satellite systems for communication/navigation, distributed radar, and formation flying optical interferometry
  - Space-based sensing to include visual and IR Earth imaging, multispectral Earth imaging and mapping, ballistic/cruise missile and air/ground target detection and tracking, and deep space observations/missions
- Atmospheric/space phenomenology and monitoring to include solar wind, magnetosphere and global ionospheric monitoring, mid-Earth orbit radiation belt monitoring, and Earth sciences
- Satellite servicing to include visual and broad-spectrum inspection and diagnostics (RF, IR, and other non-contact inspection), and orbit changing (via tether attachment or space tugs)
- Planetary exploration and services for Earth or other planetary bodies, using a micro-communications and GPS/navigation system
- Low-cost space system and sensor technology testbeds.

Additional systems/missions under study for the farther term include launch-on-demand capabilities, solar sail/large aperture configurations, on-orbit power generation and resupply, and space debris removal. The combination of miniaturization characteristics, processes and concepts is illustrated below.

At the same time, it needs to be understood that microsats may also have mission limitations in proportion to their weight ceilings. Individual microsats are typically restricted in capability because of the relatively large mass-fraction that must be dedicated to bus functions (such as power, communications, thermal management, attitude control, and orbit maintenance). Therefore, an important technology thrust will be to explore the capability to "host" microsat "hitchhikers" on other platforms, such as servicers or "mother ships" that remain permanently on orbit. If such a capability is achieved, military space systems could realize the best of both worlds: the low cost, ease of launch and specific capabilities of microsatellites and the high delta-V capability, higher bus power and better communications facilities aboard a host spacecraft.

Microsat Enablement of New Operational Space Paradigms

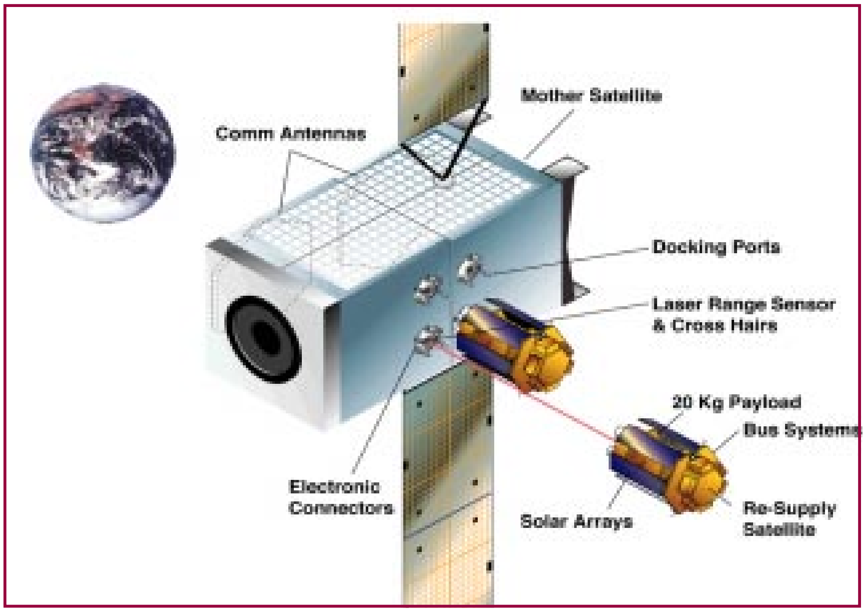


Enabling Technologies

Many on-going technology programs focus on reducing size, weight and power requirements of satellites and their subsystems. These include:

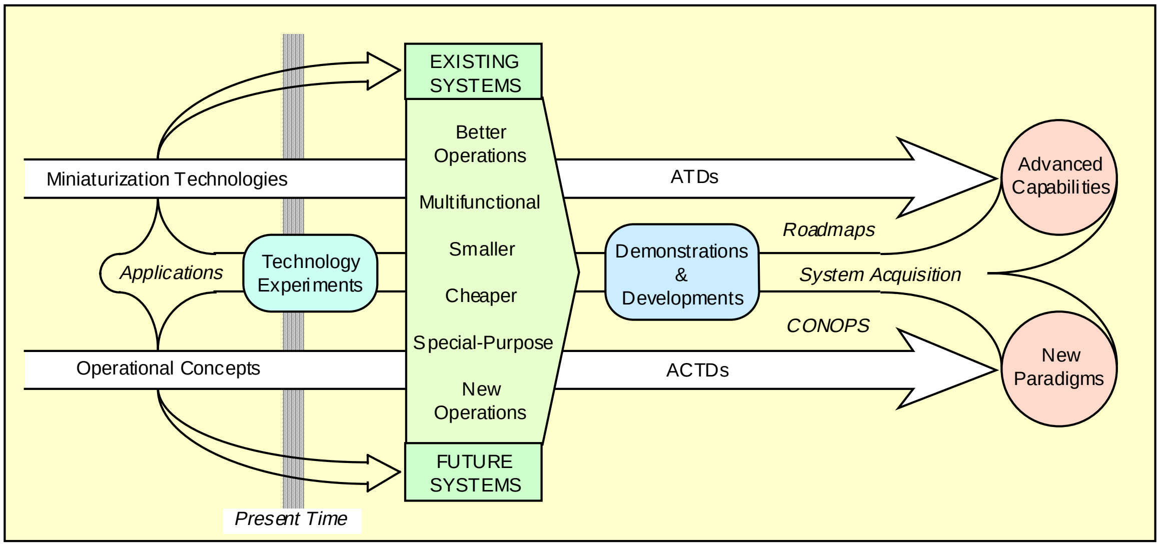
- Advanced micro-propulsion systems providing higher specific impulse (Isp) and increased total change in velocity (delta V) (respectively, the propulsive mass efficiency and the effort required to get from one location to another in space
  - Engines/devices – electric, solar, thermal, chemical
  - Fuels/propellants
- Micro-inertial attitude sensing and control subsystems
- Autonomous satellite control, to enable:
  - Formation flying
  - Close proximity maneuvering
- Lightweight, efficient, electrical power systems
  - Inertial energy storage (flywheels)
  - Fuel cells
  - Lithium ion/polymer batteries
  - Ultra-lightweight deployable solar cells/arrays/concentrators
- High specific power electrical subsystems
- Lightweight, multifunctional structures
- High-precision micro-robotic devices
- Onboard processing
- Micro-navigation systems
- High-density interconnected electronics
  - Radiation-hardened micro-processors
  - Optical buses with high-capacity data storage
  - Superconducting electronics
- Modular electronics
- Miniaturized, scalable, power-efficient electronic components and mechanisms
  - E.g., fiber optics, optoelectronics, photonics, micro-electromechanisms (MEMS)
- Miniaturized thermal control and management devices and concepts
  - Cryocoolers
  - Heat pipes
  - Superconducting electronics (to eliminate need for cryocooling)
- Lightweight active/passive sensors
  - Solid-state electronically steerable beams
  - Efficient transmit/receive modules
- Low-cost manufacturing tools and techniques.

Of these technology efforts, very few are pursued specifically for microsatellites, but microsatellite concepts are leveraging them to achieve significant advances in mission applications and capabilities. The interrelated themes of this generation-long process are depicted in the following diagram.



Orbital Express Concept

From Technology Concepts to Deployed Capabilities



At present, the DoD is at a relatively early stage of exploration of microsat classes. It will take several years of project results to assure which systems and operational concepts to pursue into full acquisition. At the same time, the potential payoffs for the far term are sufficiently high that a variety of experiments and early technology demonstrations are currently funded. These are summarized in the following section.

Current Microsat Technology Applications

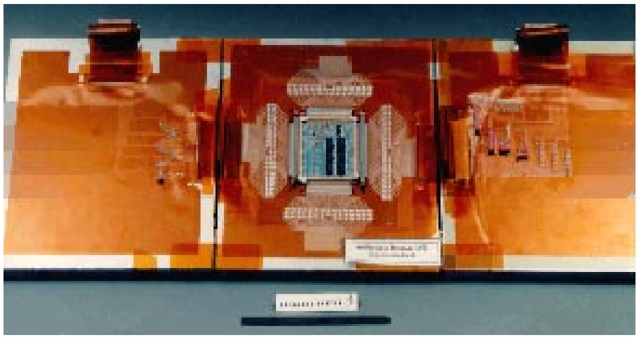
Space System Demonstration Testbeds

Microsatellites have provided space system developers a lower-cost method to demonstrate and space-qualify advanced technologies. A variety of these programs are routinely executed by both NASA and the DoD. Recent programs include the joint U.S.-UK STRV-1A and -1B, two 55-kg microsatellites placed in a geostationary transfer orbit using the Ariane secondary payload ring, the AFRL MightySat I, a 68-kg satellite launched to LEO as a Space Shuttle “hitchhiker” experiment, and the 300-lb MightySat II.1 launched on the Orbital/Suborbital Program’s Minotaur.

These missions demonstrated advanced sensors, space environment monitoring and advanced miniaturized subsystems, and show the value of microsatellites as low-cost, sophisticated DoD space technology test platforms.

Multifunctional Structures

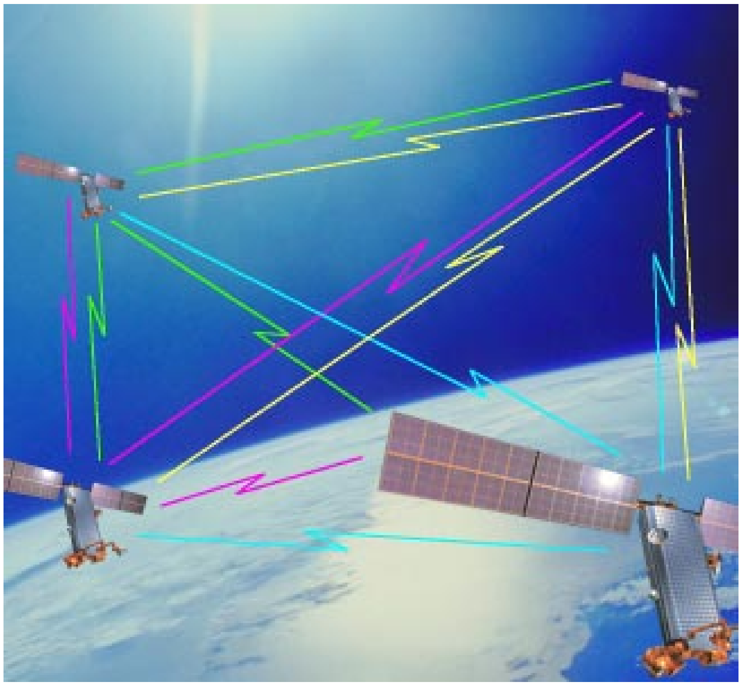
An example of a high-leverage technology that promises to revolutionize future spacecraft design and fabrication is multifunctional structures. In this approach, the cabling and interconnects are replaced by multi-layer copper/polyimide film and flex jumpers bonded on the structural substrate, ingeniously resulting in a cable-less spacecraft. Each layer of the multifunctional network performs a specific electronic function: power, ground, control, and data transmission. Most of the spacecraft bus function can be integrated into the structure. Electronic components are mounted directly on the spacecraft structure without the use of printed circuit boards and associated enclosures and brackets, resulting in unparalleled weight savings. System studies have demonstrated that application of multifunctional structures, along with other emerging technologies such as advanced multi-chip modules, thin-film photovoltaic solar arrays and solid-state batteries, can reduce the dry weight of a typical satellite bus by a factor of 10.



Similar technology investment is being made in payload sensors. Such efforts include integration of neural processing chips mated to sensor pixel arrays, integration of miniature transmit and receive modules and MEMS switches into RF antenna panels, and the miniaturization of the associated electronics. Alternate payloads include inflatable antennas that can be packaged for launch in small volumes, and the associated technology efforts include space-durable inflatable materials, rigidization processes, and miniaturization of the inflation system.

Collaboration and Distributed Processing

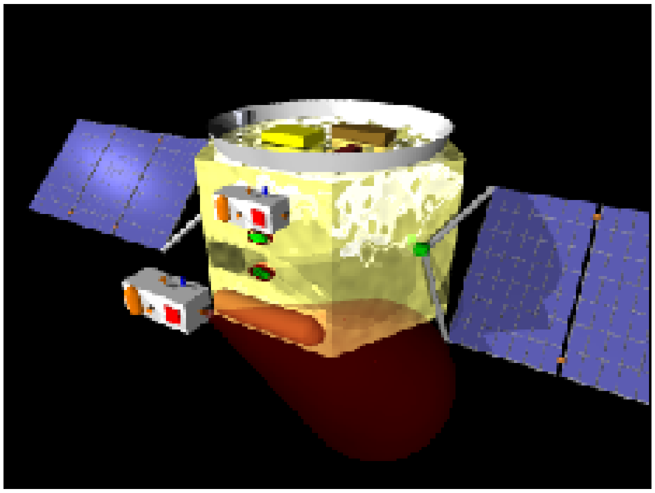
Microsatellites in formations would require knowledge of their relative positions and the ability to maintain that formation over many years. Active research areas include integrated GPS/communication/ranging, micro-propulsion, and minimum-fuel formation flying. In addition, scientists are investigating the flocking behaviors of birds to explore application to satellite formations. Optimal data transfer and processing strategies are also being examined to maximize efficiency of on-orbit processing by creating a parallel computing network within the formation. These processing algorithms incorporate flexibility to address the loss or addition of satellites to the formation, mission prioritization and scheduling, as well as reconfiguring the formation to perform alternate missions. Also, since multiple microsatellites could replace large monolithic satellites, autonomous control algorithms are being developed to reduce ground control requirements.



Autonomous Proximity Operations

Critical requirements for on-orbit servicing are autonomous navigation, close proximity maneuvering, and fail-safe collision avoidance. Neural-based approaches have steadily improved in learning rates and operational performance over the last two decades. These have the potential of autonomously performing host spacecraft identification and orientation determination, intercept optimization, and soft docking. However, for the foreseeable future, maneuvering in the proximity of national space assets may still require man-in-the-loop operations to minimize risk.

On-Orbit Servicing (Inspection, Supply, and Repair)



Capable servicing microsatellites could inspect, deliver new equipment, and effect repairs on satellites to extend their life or capability. The satellite to be repaired would be designed with an open architecture and external ports, much like the expansion slots in a personal computer. The servicing microsatellite would autonomously dock with open ports on the host satellite. The new equipment, like processors, memory units, or batteries, would be recognized and the system reconfigured to account for it in a "plug-and-play" fashion. Additional examples of repair include decontaminating optics, reapplying coatings, reinforcing weak or damaged structures, and lubricating joints. These upgrades would extend operational life and keep the satellite current with changing technology, threats, and mission requirements. An alternative strategy for inspection and repair would use small adjunct satellites to launch with the primary satellite and then separate to perform servicing as required.

Low-Cost Manufacturing

A critical factor in realizing the microsat vision is reducing their cost by a factor of 10. Today's satellites are expensive, one-of-a-kind systems with considerable non-recurring engineering and touch labor. Modularization strategies and automated manufacturing processes need to be developed to enable low-cost mass manufacturing of all microsat classes. Commercial satellite constellations such as Iridium and OrbComm have already taken the first steps in this direction. Capitalizing on this approach, the DoD recently initiated studies to minimize microsatellite design and fabrication costs. The current strategy is to leverage existing design and manufacturing approaches being applied today for limited-production items (such as executive jets, high-end automobiles, and missiles) to demonstrate that highly complex microsatellites can be built in quantities of 100 for less than $1M each. At this low cost, microsatellites could be used for a wide range of on-orbit inspection, surveillance, and other missions with lifetimes of a few days or weeks and be considered essentially disposable.

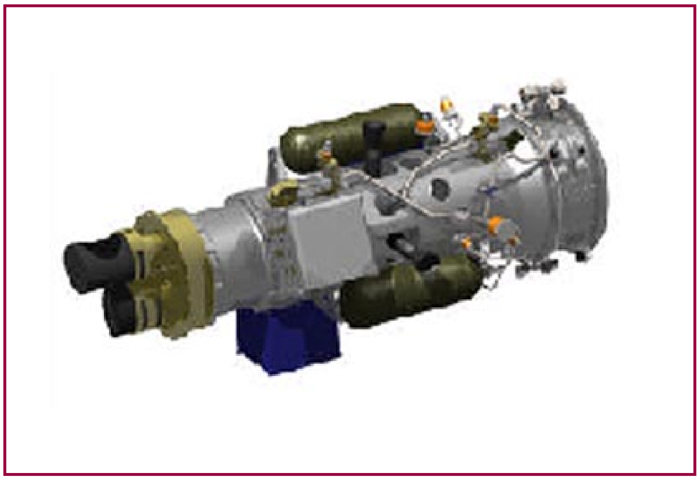
Tactical Space-Based Sensing

As microsatellite capabilities expand and their costs decrease, they will become ideal temporary, low-cost space assets for rapid deployment into LEO. Example missions include quick-response SIGINT, low-resolution imaging, communications relays, SAR, and MTI to U.S. forces. Often, the national resources available to provide such monitoring are either not properly positioned to provide the needed coverage, or have been preempted for other high-priority purposes. Being able to quickly place an imaging asset in an appropriately selected orbit for a limited-duration mission could be extremely valuable to battlefield commanders. Imaging microsats could also support disaster relief or peace-keeping operations where other remote-sensing systems are not available.

Low-Cost, Rapid Microsat Launch Capability: A key enabler of tactical surveillance using microsatellites would be the ability to launch on demand. A near-term solution is to use air-launched missiles to provide rapid and inexpensive access to space. Initial studies at AFRL have examined an F-15-launched 3-stage missile for delivery of a 30-40 kg payload to LEO within a matter of hours. The microsatellites are envisioned as modular and robust enough to be stored and readied at the launch site in several hours, and then reconfigured for the required mission. Launch-on-demand also provides constellation augmentation resources to replace destroyed or damaged assets, or for surge capability in times of high demand. Alternative applications include rapid on-orbit inspection and repair of malfunctioning satellites or inspection of unknown satellites. This concept could be further explored using existing missile technologies, leveraging significant development completed under the anti-satellite (ASAT) program of the early 1980s.

AFRL Experimental Satellite System (XSS)

The XSS program evolved from the joint DoD, DOE and BMDO activity that produced the Clementine II microsatellite technology program started in FY 1996. XSS is currently a flight experiment to demonstrate increasing levels of autonomous on-orbit inspection, docking, and servicing. Key technologies are high-performance propulsion, autonomous proximity algorithms, and next-generation optical sensors. XSS-10 will demonstrate rendezvous, proximity maneuvering, and visual inspection of the Delta second stage that deployed it.

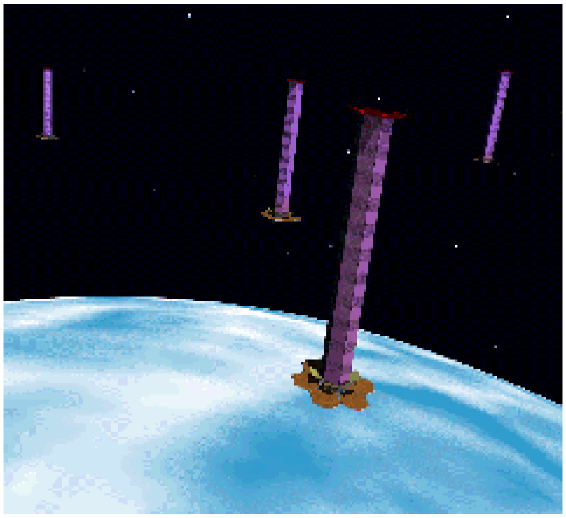


Distributed Satellite Systems

A number of distributed satellite concepts would be enabled by highly capable microsatellites. One such concept envisions formations of satellites that cooperate to perform the function of a larger, single satellite. Each smaller satellite communicates with the others and shares the processing, communications, and payload or mission functions. The required functionality is thus spread across the satellites in the formation, the aggregate forming a "virtual satellite." An important aspect of these formations is the ability to synthesize a large aperture. Since the satellites are not physically connected, they can be separated over large baselines — which is not feasible for monolithic apertures.

This system architecture is also appealing for its adaptability, reliability, and survivability. As neither the geometry of the cluster nor the number of satellites in the cluster is fixed, the cluster configuration could be changed to perform such missions as moving target indication (MTI) using space-based radar, mobile or jam-resistant communications, precise geolocation, or signal intelligence (SIGINT). The growth potential of these virtual satellites appears attractive for high-value, high-cost missions. The system performance may be slowly increased over time with a phased deployment, or capabilities tailored to meet evolving threats or world conditions. The deployment cost could be spread over several years while still providing acceptable but ever-increasing levels of performance. Similarly, the loss of one or more satellites in the formation would have but limited impact on system performance.

AFRL TechSat 21 Program: The Air Force Research Laboratory has initiated the TechSat 21 program to develop the technologies needed to enable such distributed satellite systems. Sparse aperture sensing was selected as a reference mission to help identify technology requirements and to allow an easy comparison to conventional approaches.



Basic research is being conducted in sparse aperture signal processing, micro-propulsion, formation flying, collaborative control, spatial ionospheric effects, and MEMS for spacecraft. Technology efforts are focused on lightweight, low-cost microsatellites, especially those critical to collaborating formations, such as precise differential GPS positioning, intersatellite ranging and communication, high-capability power systems, lightweight solid-state phased array antennas, micro-propulsion, advanced electronics packaging, multifunctional structures, and advanced thermal control. The program culminates in a flight experiment of three microsatellites that launch in early 2003 to validate key features of distributed satellite systems. This formation will be reconfigurable and will perform sparse aperture sensing, geolocation, and secure communications.

An alternative distributed satellite architecture would use sparsely distributed micro- or nanosatellite (1-10 kg) constellations to make concurrent observations of the space environment in the ionosphere, through the radiation belts, or out to the limits of the magnetosphere. NASA is exploring a variety of such mission concepts to make spatial and temporal measurements of atomic oxygen, micrometeorites and debris, the solar wind, space radiation, and magnetic fields.

NASA Space Technology 5 (ST-5): ST-5 is named the Nanosat Constellation Trailblazer and consists of three 20-kg satellites, sized 16" across and 8" high, which demonstrate feasibility of constellations of 100 or more sparsely distributed nanosatellites to make spatial and temporal space environment measurements. The experiment objectives include 3-D mapping of the Aurora, large-aperture astronomy missions, and stereoscopic viewing of the Earth. The satellites are highly integrated with miniaturized electronics, extendable booms and antennas, micro-subsystems for communication and attitude control, high-performance mini-thrusters, and a broad range of micro-instrumentation. This flight demonstration is the fifth in the series of New Millennium missions and will launch in 2003.

Assessment and Findings

It should be recognized that what is ultimately wanted is better and more affordable spacecraft rather than their miniaturization as an end in itself. The pursuit of miniaturization at the component level has already had, and will continue to have, just such a payoff for larger spacecraft — especially in reducing their launch and on-orbit maneuvering costs. From this point forward, the pursuit of the several classes of microsat (from smallsats down) is geared toward the achievement of new capabilities leading to new operational paradigms; i.e., the microsat "vision" is for combinations of characteristics and capabilities that will enable new "ways of doing business" operationally.

Steady advances in miniaturized electronics and other satellite subsystems, combined with innovative designs, are creating new concepts for space mission architectures. These have the potential to revolutionize some space missions over the long term and reduce equivalent satellite life-cycle costs up to tenfold, while retaining performance equal to or better than current systems'.

Microsats today are where personal computers were in the late-1970s. Networks of workstations and personal computers (PCs) rapidly replaced mainframes as most primary processing platforms and ushered in such unforeseen events as a PC on every desk and a decade of exploding commercial internet functions. Similarly, we have barely scratched the surface of the potential and utility of microsatellites and their real national security space payoffs remain uncertain. Proper exploration of their potential will continue to need significant and sustained investment on the part of both government and industry for the foreseeable future, both to sponsor their enabling technologies and to fund the progressive in-space experiments and demonstrations needed to assure feasibility and reduce acquisition risk.

In summary, with due regard for limitations as well as benefits from smallness, the future of microsats is currently projected to lie in special niche areas of operation for the near- to mid-term, but potentially in new operations altogether for the far term and beyond.

Recommended Investment Strategy

For the Near Term: Continue investments associated with miniaturization. The near-term payoff will continue to be lighter and smaller satellites for current and emerging mission applications. These investments will result in:

- Launch capabilities more flexibly tailored to different classes of small- and microsats and to enable launch on demand
- Continuing reductions in overall launch costs, thereby facilitating access to space as the basis for all missions
- Longer life on orbit, characterized by lower costs and greater functional efficiency
- Increasingly multifunctional payloads, leading to increasing multimission utility
- The freeing up of valuable launch assets for more or other payloads.

For the Mid- to Far Term: Continue present investments in microsatellite applications. The eventual payoffs will be:

- New capabilities to improve or augment performance of existing missions and to enable performance of new missions
- The ability to "populate" space with operational and supporting infrastructure and support capabilities, such as on-orbit servicing, spacecraft inspection and troubleshooting, and replenishment of consumables
- New concepts of operation, such as cluster and formation flying, microsat C3 and support by host satellites, and, should policy dictate, support of force applications for terrestrial and space operations.

13. Space Technology Demonstrations

General

All technology demonstrations have three major purposes:

- To test new items in their prospective space environment
- To reduce the risk of developing and acquiring the systems that will use them
- To explore the ability of new or different technologies to enable innovative or unique applications and operational capabilities.

Tests and demonstrations are normally inherently expensive, but their overarching benefit is to help determine technical feasibility and operational utility of key technology applications, thereby reducing both acquisition risk and costs for savings several times the value of the original tests.

Space technology demonstrations have additional costs and benefits. First, as their operational environment is in space, they must incur the additional costs and risk of launch to orbit before they can reach their test "site" — usually in an orbit consistent with mission-required characteristics. Secondly, if the test item's performance is successful, a significant payoff in risk reduction is achieved, which in turn translates into greater levels of technical confidence that the technology can be applied without undue inherent risk. When the major costs of acquiring and deploying space systems are considered, the value of such increased assurance equates to a high level of prospective cost avoidance. Thus space technology demonstrations and similar tests from components to entire spacecraft *in situ* is absolutely essential in the way the nation "does business" with respect to testing new technologies and concepts and acquiring improved space capabilities.

Assessment

There are several avenues to test new space technologies on-orbit, ranging from dedicated launches to "hitchhiking" aboard other system launches or the Space Shuttle. Typically, space experiments today are developed in research laboratories; some are flown on dedicated lab-designed satellites, but most lack the funds either to launch or test them in space. The laboratories then package experiments together to meet overall cost feasibility criteria for a Space Test Program (STP) launch and then use that to surmount the major launch cost hurdle. This has become a standard model for DoD experiments. Currently, several space technology demonstrations are planned as "pathfinders" to future systems (see also Appendix G).

As S&T budgets have become increasingly constrained, the resources to fund the basic spacecraft bus that supports a set of experiments, the integration of experiments into the host spacecraft, the launch costs themselves and the on-orbit operational and support costs have fallen almost exclusively upon the STP. Meanwhile, the STP has itself become increasingly constrained to the point where it is now severely limited in its ability to meet demand for launch services. Currently, the flow of experiments actually flying in space has been reduced to a fraction of past years', with the majority now using the Space Shuttle as their only practical launch option. When major programs such as missile defense fund an experiment, the line of hopeful "hitchhiker" payloads grows significantly because the launch cost will be borne by another program.

The STP is now typical of the fiscal forces confronting potential experimenters. The original funding level was programmed to support a small launch vehicle every two years and a medium launch vehicle every four years. The associated launch support, payload integration and ground support costs were also included. Funds to support flying experiments on the Shuttle were budgeted as well. Today, while the STP budget has remained level or declined, the cost for the two classes of launch vehicle have grown by more than 30 percent. This has significantly limited the STP's ability to support current and future defense missions.

The DoD has explored the use of special payload adapters or "collars" on existing launchers as sources of lift for experiments; these should help ease the backlog in experiments awaiting launch. However, whenever additional payloads are added to a launch, it adds risk for the primary payload. We expect to use future Evolved Expendable Launch Vehicle (EELV) launchers as lift sources for experiments, but they will be limited to the availability of space in the EELV fairing and to the orbit planned for the primary payload.

As for space-bound Advanced Technology Demonstrations (ATDs) and Advanced Concept Technology Demonstrations (ACTDs), they tend to focus on validating new concepts and approaches using existing payloads and assets and are not typically a source of support for flying experiments.

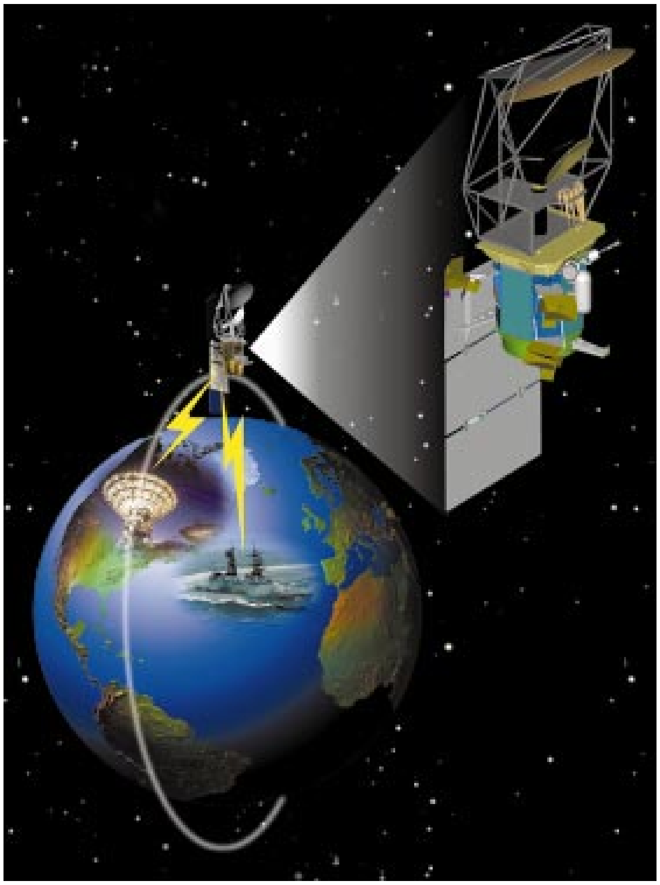
Findings

- The decline of S&T funding during the nineties has resulted in fewer technologies mature enough for demonstration in space. This, combined with higher satellite and launch cost, has exacerbated the problem. While the average of major space demonstration missions used to be two or more per year, the current rate is less than one per year. The Department has now increased S&T funding; however, the lag in space demonstrations will continue over the near term.
- Most S&T missions are now dependent on either the Space Shuttle or the launch of a major defense system, with experiments accommodated according to the space available on the host launcher. The Shuttle remains the primary ride to space for most experiments. Low cost and availability are the key factors
- The use of payload adapters would facilitate the incorporation of space experiments on available launch vehicles.

Advanced Research and Global Observation Satellite (ARGOS)

Largest Air Force R&D satellite to date for the conduct of upper atmospheric observations and technology demonstrations.

Coriolis



Coriolis is supporting risk reduction of the NPOESS environmental sensor and will also demonstrate a solar activity monitor.

14. Summary

Approach and Activity

Pursuant to §1601 of the *National Defense Authorization Act* for FY 2000, the DoD has developed this Space Technology Guide. Its overarching objective is to:

- Research and identify enabling technologies that will support emerging defense space systems and missions during the next 20 years and beyond
- Identify those space-relevant technologies that "must be done and must be done right" to preserve our national security space preeminence well into the 21st century.

The STG's time frame covers the next 20 years, to about 2020, from the perspective that, just as our current space capabilities have resulted from technologies developed in decades past, our future capabilities will depend on the technologies under development now. Moreover, for the U.S. to prevail in a world that is increasingly moving both commercial and military functions to space, the DoD needs to emphasize the development of those technologies that will provide the most leverage in meeting national security space objectives.

In first identifying and then selecting the many space-relevant technologies under way or planned, we:

- Referred to top-level defense space planning community documents for their perspectives on operational needs, concepts and technologies for the future
- Researched the S&T community's documents for requisite technology projects within both DoD and other Federal government agencies
- Solicited views and initiatives from the space industry
- Identified technology areas and projects being pursued via interagency collaboration.

Special attention has also been paid to two areas of Congressional interest:

- Microsatellite technologies, which have emerged from the preexisting trend towards miniaturization of components and spacecraft
- Space technology demonstrations, which have been increasing in relative cost and declining in frequency, and which are now dependent largely on other programs' launch opportunities or room on the Space Shuttle to be launched into space.

Findings and Observations

- There is an extensive number of enabling technologies, covering much of the S&T spectrum, that contribute to the continuing preeminence of U.S. national security space capabilities. A few of these technologies are exclusive to space applications, but most comprise the extensive menu from which terrestrial as well as space applications are continually being made. With varying emphasis and often in partnership with other Federal agencies and the private sector, they are the space-relevant technologies in which the Department invests the major part of its research and advanced technology resources.
- Of this large number, a select list represents cross-cutting technologies that not only support multiple mission areas but do so in ways that promise major advances in capability over a relatively short time — to the extent that they represent the possibility of breakthroughs to new levels of capability or system effectiveness, thus amplifying their return on investment. These have been identified as **key enabling technologies** (and are listed on p. 14-2).
- Based in part upon information provided by representatives of the space industry, some technologies are government-unique and some others are not commercially viable. If such technologies are to be developed and applied, then the government must provide the investment. For example, many sensor applications are unique to government requirements and hence are funded solely by the government. Similarly, there are additional technologies that are essential for government missions but which may have or develop commercial application as

Key Enabling Technologies

- **Propulsion / Propellants**
  - Advanced cryogenic
  - Full flow cycle
  - Advanced solid rocket motors (SRMs)
  - Combined-cycle (air-breathing engines + rocket)
  - Electric (Hall effect, ion, plasma thrusters)
  - Solar thermal/chemical
  - High-energetic, low-hazard, non-toxic, storable propellants
- **Electric Power**
  (Solar / Chemical / Mechanical;
  i.e., cells/batteries/flywheels)
  - Higher energy density and efficiency
  - Longer life, higher duty cycle
  - Lightweight, thermally stable
- **Structures and Materials**
  - Lightweight, high-strength composites and ceramics
  - Multi-functional, adaptive structures
  - Processing techniques
  - Vibration and thermal control
  - Thin films and environmentally protective coatings and insulation
- **"Thinking" Satellites**
  - Autonomous control
  - Self-assessment/correction
  - Threat detection
  - On-board supercomputing
  - On-orbit robotics
- **More Precise Clocks / Time Sources**
  - Laser/optical, atomic
- **Communications**
  - Lasercom
  - Wideband microwave/millimeter wave
- **Antennas**
  - Large, light, controllable, adaptive space-time
  - Higher frequency
  - Steerable beam phased arrays
  - Higher-efficiency amplifiers
- **Synthetic Aperture Radar (SAR)**
  - Large, light, high-power
  - Interferometric
- **Electro-optic (EO) Sensors**
  - Large, light, deployable, stable, adaptive optics
  - Multi-, hyper- and ultraspectral
  - Large-scale, high-quality focal plane arrays (FPAs)
  - Light, long-life, high-efficiency cryocoolers
  - Uncooled sensing materials
- **Signal Processors (Transmitters / Receivers)**
  - Higher signal-to-noise ratio
  - Higher density devices and circuitry
  - Higher efficiency analog-to-digital (A/D) conversion
  - Advanced encryption technologies
- **Microelectromechanical Systems (MEMS) / Microelectronics / Photonics**
  - Switches and actuators
  - Gyroscopes (e.g. fiber-optic gyros)
  - Inertial measurement units (IMUs)
  - Accelerometers
  - Non-volatile logic and memory
  - Opto-electronics
- **Radiation Hardening**
  - Techniques and components
  - Memory, processors, semiconductor materials
- **Ground Processing**
  - Data fusion
  - Advanced algorithms for processing and exploitation

While these key enabling technologies represent a general focus for Department activity and are deemed prerequisite to far-term space preeminence, they should not be pursued at the expense of the wide range of S&T work that is conducted across the DoD components — much of which has not been specifically identified in this Guide but which also represents important space potential at varying stages of maturity.

well; however, the cost of their development is usually so high that industry cannot make a business case for maturing them commercially. Examples include the Global Positioning System, or development of new propulsion concepts. (These private sector views were also considered in identifying the key enabling technologies.)

- The notion of partnerships must be viewed, considered and applied with care. Intra-government partnerships have usually worked well. With the emergence of the Space Technology Alliance; the Air Force Space Command, National Reconnaissance Office and National Aeronautics and Space Administration Partnership Council; and the brokering of partnerships by the Space Test Program, the government has fostered numerous highly productive collaborations that have minimized duplication and leveraged joint resources. Industry/government partnerships have had less success as the latter is driven primarily by national policy considerations while the former is driven by economic market forces. Again, national security space requirements are often unique, while the business case for industry has been risky at best. Typically, the most effective industry-government partnerships have been in areas like launch vehicle propulsion, spacecraft bus and spacecraft propulsion technologies, where companies can readily leverage the joint investment into their commercial market segments and strategic plans. From the DoD perspective these activities have best been fostered by coordinated government/industry-funded programs like the Integrated High Payoff Rocket Propulsion Technology program (IHPRPT).
- The short-term payoffs of the investments in microsatellite technologies will be seen in the application of miniaturization to existing systems to enhance performance and/or capability. For example, smaller lighter components may translate into more fuel for longer life on orbit. Such benefits are immediate and achievable in the near-term. Over the longer term, we expect to see significant microsatellite contributions in special-purpose and "niche" roles, to include enabling new operational capabilities of major significance and cost-effectiveness. For example, a microsatellite or microsat constellation could enhance revisit times and augment imagery of a specific geographic area during a contingency situation. However, the broad application of microsatellites to the full range of national security missions is unlikely even in the far term. Some limitations imposed by the laws of physics will require larger platforms for the foreseeable future.
- Of major concern: space-based technology demonstrations are expected to continue to decline due primarily to budgetary constraints. Major experiments and demonstrations are typically expensive, even when the launch segment costs are manageable. Military science gets to orbit when other major missions (such as missile defense) represent the prime payload and bear the bulk of the costs. Otherwise, experiments must either be tested on the ground (which has significant limitations and risks), be subject to the attrition of budget priorities, or be cancelled when no longer considered priority candidates for limited funding.

The STG itself provides an unconstrained approach via its focus on technology projections well beyond the FYDP, but it is not in a position to address

Space Orbit Transfer Vehicle (SOTV)
High energy transfer vehicle

funding and budgetary implications for the next 20 years. While increased funding of many promising areas could accelerate the possibilities for success, specific S&T breakthroughs cannot be guaranteed by money alone. Instead, a balanced and steadily supported S&T program provides the greatest likelihood of success and flexibility in advancing defense space capabilities.

Collected Recommendations

1. Continue to pursue a balanced S&T program to provide the breadth and flexibility to support a wide range of space technology applications to meet current and emerging needs.
   - Continue to incorporate private sector advances where appropriate in pursuit of this broad S&T program so as to leverage government applications from a broader commercial base.
   - Continue to miniaturize components so as to lower launch costs, extend on-orbit life, upgrade replacement satellite performance, enable new capabilities for satellites of all sizes, and develop new operational paradigms.
   - Sustain investment in advanced technologies to increase reliability, durability, and payload flexibility and reconfigurability.
   - Pursue microsatellite concepts via experiments and demonstrations keyed to proving the component technologies and demonstrating military utility.
2. Focus enough government resources on the key enabling technology areas identified above to assure their timely availability for system and operational applications.
   - Leverage private sector technology investments where possible, but recognize that there are areas where national security applications require unique features and capabilities, and that the government must take the lead in their development.
   - Recognize that, for such cross-cutting technologies to be available when needed, focused but stable investment is required as a prevailing condition.
3. To facilitate technology transition, continue to structure and budget for space experiments and demonstrations as a key part of requisite technology application, maturation, and proof of military utility.
   - Recognize that experiments and demonstrations represent long-lead, risk-reduction opportunities prior to full-scale development and application, which otherwise could be even more risky and costly.
   - Collaborate where practical via partnerships to share costs and broaden the basis for support.

Conclusion

The relationships of the operational space community's projected space missions and functions and the S&T community's space-related technology activities are depicted in the two-page illustration on pages 14-5 and -6. From the left of page 14-5, operational needs, emanating from Joint Vision 2010/2020, have been implemented in USSPACECOM's *Long Range Plan* for 2020. From the right of page 14-6, the space technology base illustrates the S&T documentary progression from basic research through successive development stages, to include interaction with the operational and acquisition communities, both to tailor technological effort to operational needs and to assure that needs are attainable and affordable. The area of convergence is at the Departmental level, where, to meet STG objectives, technology-dependent space missions help to define the key technologies that will enable the successful performance of their future functions. If pursued with well-planned and sustained investment, their projected effectiveness and synergies will do much to achieve our national security space objectives for at least the first half of the 21st century.

DoD Space Technology

OPERATIONAL NEEDS

JOINT VISION 2010 and 2020

CONCEPTS

DOMINANT MANEUVER
+
PRECISION ENGAGEMENT
+
FULL DIMENSIONAL PROTECTION
+
FOCUSED LOGISTICS

FULL SPECTRUM DOMINANCE

JOINT WARFIGHTING CAPABILITY OBJECTIVES

1. **Information Superiority**
2. **Precision Force**
3. **Combat Identification**
4. **Theater Missile Defense**
5. **Military Op'ns in Urban Terrain**
6. **Joint Readiness**
7. **Joint Countermine**
8. **Electronic Warfare**
9. **Information Warfare**
10. **Chem/Bio Agent Detection**
11. **Real-Time Logistics Control**
12. **Counter-proliferation**

USSPACECOM VISION (LRP for 2020)

CONCEPTS-Objectives–Tasks

CONTROL OF SPACE

- Assured Access -
– Transport Mission Assets –
– On-Orbit Operations –
– Service and Recovery –

- Surveillance of Space -
– Detect (all) –
– Track (all) –
– Characterize (all) –
– Classify (threats) –
– Catalog/Monitor (sats) –
– Disseminate/Distribute –

- Protection -
– Detect & Report Threats/Attacks –
– Withstand & Defend –
– Reconstitute & Repair –
– Assess Mission Impact –
– Identify, Locate & Classify (threat/attack sources) –

- Prevention -
– Detect Use (of systems) –
– Assess Mission Impact –
– Timely/Flexible Reaction –

- Negation -
– Target Identification –
– Weaponeering –
– Operations Cycle –

GLOBAL ENGAGEMENT

- Integrated Focused Surveillance -
– C4ISR –
– Detecting, Cueing, Fusing –
– Warning (of threats) –
– Tasking –
– Classifying, Characterizing, Discriminating –
– Monitoring, Cataloging, Assessing–
– Tailoring (products to needs) –
– Dissemination (of support) –

- Missile Defense -
– Battle Management –
– On-Demand Missile Defense –
– Full Spectrum Engagement –
– Combat Assessment –

- Force Application -
– BMC3 –
– On-Demand Force Applic'n –
– Flexible Force Application –
– Flexible Effects –
– Combat Assessment –

FULL FORCE INTEGRATION

GLOBAL PARTNERSHIPS

CRITICAL SPACE TECHNOLOGY

DoD SPACE TECHNOLOGY GUIDE

TECHNOLOGY AREA NEEDS

KEY FUNCTIONS

SPACE TRANSPORTATION

SATELLITE OPERATIONS

NAVIGATION

COMMAND, CONTROL, and COMMUNICATIONS

ENVIRONMENTAL MONITORING

INTELLIGENCE, SURVEILLANCE, and RECONNAISSANCE

SPACE CONTROL
Surveillance of Space
Protection
Prevention
Negation

FORCE APPLICATION
Deterrence
Defensive
Offensive

KEY ENABLING TECHNOLOGIES

(Must Do Right, and In Time)
DoD-unique, or DoD as lead

PROPULSION / PROPELLANTS

ELECTRIC POWER (Solar / Chemical / Mechanical)

STRUCTURES and MATERIALS

"THINKING" SATELLITES

PRECISE CLOCKS / TIME SOURCES

COMMUNICATIONS

ANTENNAS

SYNTHETIC APERTURE RADAR (SAR)

ELECTRO-OPTIC (EO) SENSORS

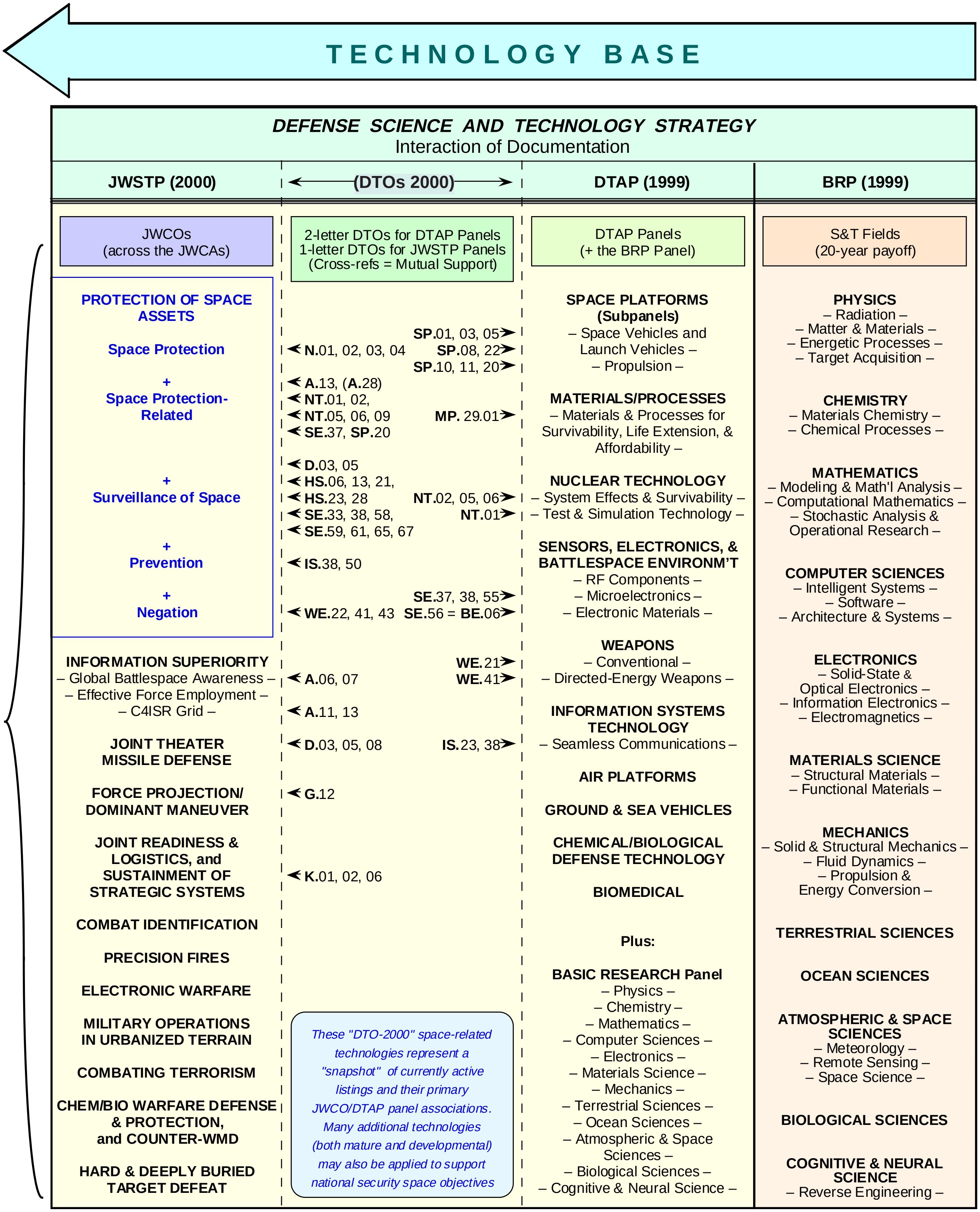
SIGNAL PROCESSORS (Transmitters / Receivers)

MICROELECTRO-MECHANICAL SYSTEMS (MEMS) / MICRO-ELECTRONICS / PHOTONICS

RADIATION HARDENING

GROUND PROCESSING

Guide: Document Flow



TECHNOLOGY BASE

DEFENSE SCIENCE AND TECHNOLOGY STRATEGY
Interaction of Documentation

JWSTP (2000)

JWCOs
(across the JWCAs)

PROTECTION OF SPACE ASSETS

Space Protection

+
Space Protection-Related

+
Surveillance of Space

+
Prevention

+
Negation

INFORMATION SUPERIORITY
– Global Battlespace Awareness –
– Effective Force Employment –
– C4ISR Grid –

JOINT THEATER MISSILE DEFENSE

FORCE PROJECTION/ DOMINANT MANEUVER

JOINT READINESS & LOGISTICS, and SUSTAINMENT OF STRATEGIC SYSTEMS

COMBAT IDENTIFICATION

PRECISION FIRES

ELECTRONIC WARFARE

MILITARY OPERATIONS IN URBANIZED TERRAIN

COMBATING TERRORISM

CHEM/BIO WARFARE DEFENSE & PROTECTION, and COUNTER-WMD

HARD & DEEPLY BURIED TARGET DEFEAT

← (DTOs 2000) →

2-letter DTOs for DTAP Panels
1-letter DTOs for JWSTP Panels
(Cross-refs = Mutual Support)

SP.01, 03, 05 →
← **N**.01, 02, 03, 04 **SP**.08, 22 →
SP.10, 11, 20 →
← **A**.13, (**A**.28)
← **NT**.01, 02,
← **NT**.05, 06, 09 **MP.** 29.01 →
← **SE**.37, **SP**.20
← **D**.03, 05
← **HS**.06, 13, 21,
← **HS**.23, 28 **NT**.02, 05, 06 →
← **SE**.33, 38, 58, **NT**.01 →
← **SE**.59, 61, 65, 67
← **IS**.38, 50
SE.37, 38, 55 →
← **WE**.22, 41, 43 **SE**.56 = **BE**.06 →
WE.21 →
← **A**.06, 07 **WE**.41 →
← **A**.11, 13
← **D**.03, 05, 08 **IS**.23, 38 →
← **G**.12
← **K**.01, 02, 06

These "DTO-2000" space-related technologies represent a "snapshot" of currently active listings and their primary JWCO/DTAP panel associations. Many additional technologies (both mature and developmental) may also be applied to support national security space objectives

DTAP (1999)

DTAP Panels
(+ the BRP Panel)

SPACE PLATFORMS (Subpanels)
– Space Vehicles and Launch Vehicles –
– Propulsion –

MATERIALS/PROCESSES
– Materials & Processes for Survivability, Life Extension, & Affordability –

NUCLEAR TECHNOLOGY
– System Effects & Survivability –
– Test & Simulation Technology –

SENSORS, ELECTRONICS, & BATTLESPACE ENVIRONM'T
– RF Components –
– Microelectronics –
– Electronic Materials –

WEAPONS
– Conventional –
– Directed-Energy Weapons –

INFORMATION SYSTEMS TECHNOLOGY
– Seamless Communications –

AIR PLATFORMS

GROUND & SEA VEHICLES

CHEMICAL/BIOLOGICAL DEFENSE TECHNOLOGY

BIOMEDICAL

Plus:

BASIC RESEARCH Panel
– Physics –
– Chemistry –
– Mathematics –
– Computer Sciences –
– Electronics –
– Materials Science –
– Mechanics –
– Terrestrial Sciences –
– Ocean Sciences –
– Atmospheric & Space Sciences –
– Biological Sciences –
– Cognitive & Neural Science –

BRP (1999)

S&T Fields
(20-year payoff)

PHYSICS
– Radiation –
– Matter & Materials –
– Energetic Processes –
– Target Acquisition –

CHEMISTRY
– Materials Chemistry –
– Chemical Processes –

MATHEMATICS
– Modeling & Math'l Analysis –
– Computational Mathematics –
– Stochastic Analysis & Operational Research –

COMPUTER SCIENCES
– Intelligent Systems –
– Software –
– Architecture & Systems –

ELECTRONICS
– Solid-State & Optical Electronics –
– Information Electronics –
– Electromagnetics –

MATERIALS SCIENCE
– Structural Materials –
– Functional Materials –

MECHANICS
– Solid & Structural Mechanics –
– Fluid Dynamics –
– Propulsion & Energy Conversion –

TERRESTRIAL SCIENCES

OCEAN SCIENCES

ATMOSPHERIC & SPACE SCIENCES
– Meteorology –
– Remote Sensing –
– Space Science –

BIOLOGICAL SCIENCES

COGNITIVE & NEURAL SCIENCE
– Reverse Engineering –