DEPARTMENT OF DEFENSE

DEVELOPING SCIENCE AND TECHNOLOGIES LIST

SECTION 19: SPACE SYSTEMS TECHNOLOGY

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PREFACE

The Developing Science and Technologies List (DSTL) is a product of the Militarily Critical Technologies Program (MCTP) process. This process provides a systematic, ongoing assessment and analysis of a wide spectrum of technologies of potential interest to the Department of Defense. The DSTL focuses on worldwide government and commercial scientific and technological capabilities that have the potential to significantly enhance or degrade US military capabilities in the future. It includes new and enabling technologies as well as those that can be retrofitted and integrated because of technological advances. It assigns values and parameters to the technologies and covers the worldwide technology spectrum.

The DSTL is oriented towards advanced research and development including science and technology. It is developed to be a reference for international cooperative technology programs. S&T includes basic research, applied research and advanced technology development.

SECTION 19—SPACE SYSTEMS TECHNOLOGY

Scope

Highlights

- The technologies used in space systems are generally based on those used in terrestrial and/or airborne applications but have many additional space-unique requirements and specifications that need to be satisfied. The space environment is unique, and this often forces the technologies to be modified significantly or tailored uniquely to the space environment.
- Space systems and their payloads are key elements of U.S. national security and U.S. economic power. They perform functions that were not before possible, enhance the performance of more traditional functions, and enable the development of new functions. These functions include military missions and commercial applications.
- The space environment is uniquely harsh. Space systems must be designed specifically for the shock and vibrations of launch, extreme temperatures, temperature cycling, temperature gradients, radiation exposure, and vacuum conditions, while maintaining high reliability over extended lifetimes.
- The inaccessibility of space and the cost of placing payloads in useful orbit place premiums on technologies for quality assurance, careful material selection, multifunctional structures, reduced mass and volume, reprogrammability, and autonomy.
- Many new space systems will be information overlays superimposed upon the space infrastructure. This will require flexible space system architectures, reusable constellations of satellites and/or clusters of microsatellites and nanosatellites, robust on-board processors, modular space vehicle designs, expanded cross-link and autonavigation capabilities, and efficient use of ground monitoring and control infrastructures.
- The development of microtechnologies and nanotechnologies will significantly impact many aspects of space systems, especially as these technologies contribute to reduced mass and volume and the associated reduction in overall costs.

Highlights (Continued)

- Environmental radiation effects, especially those of atomic oxygen, are of great concern in space applications. To date, a significant amount of space data has been generated and is being analyzed. Highlights include the first confirmation that higher damage results at space dose rates that at equivalent rates in ground tests.
- Improving the prediction accuracy of any space device, component, or system requires better models for gauging the response of electronics, microelectronics, sensors, and other photonic systems to the space environment. The results of ground measurements on the same part types as those being flown in space are now being combined with models of the space radiation environment, and the findings are being used to predict the performance of the identical parts. To improve future space assets, such predictions will be compared with the actual performance of the parts in the measured space environment.

OVERVIEW

Technology for space platforms includes not only the technologies related to space sensors, experimental apparatuses, electronics, communications, information handling, and data analysis, but also those technologies necessary for the spacecraft and launch systems (e.g., spacecraft power, launch vehicles, control and structural systems, and propulsion). The space sciences have traditionally used new and modified technologies to enable more ambitious missions. The commercial industries, the National Aeronautics and Space Administration (NASA), and the U.S. military complex have developed many technologies for unique and complex space applications. A quick look at space launch and spacecraft technologies illustrates the range of disciplines and functional areas for which space-unique technologies are required. These include items such as orbital mechanics, launch and transfer propulsion, launch and space vehicles, environmental protection, structures and packaging constraints, stability and control, thermal control, data and voice communications, power generation and distribution, sensors and instrumentation, electronics and computer processors, remote sensors, and ground station interfaces.

In addition to the obvious military applications, space technologies have made possible the current scientific concept of the earth as a complex system. From Apollo photographs of the earth as a blue marble to the recent shuttle-based radar images of rain tracks in the Midwest or ancient drainage structures under Middle Eastern deserts, the space perspective has revolutionized our understanding of atmospheric, oceanic, and land processes. Mankind has measured centimeter-scale distortions of the earth’s crust associated with plate tectonics; detected and monitored the polar ozone holes; begun to understand the dynamics and chemistry of the stratosphere and upper atmosphere; correlated climate variations with the Pacific El Niño and La Niña and with major volcanic eruptions; learned to use satellite radiometry to estimate global atmospheric temperature and moisture profiles; bounded solar variability; measured the components of the earth’s radiation; and used satellite observations to validate greatly improved atmospheric models for prediction of weather and climate.

In recent years, NASA’s emphasis on operations has increased while its pursuit of new technology has narrowed to focus on specific mission needs. Meanwhile, the Department of Defense (DoD) has aggressively funded industry, academia, and government laboratories to develop a broad range of space technologies. Consequently, DoD has become the primary agent of technological advancement, and industry and academia have become the primary U.S. developers of new space technologies. Many space-based sensors used today were developed through the collaborative efforts of industry/university/national laboratories and are based on DoD technologies.

Many space technologies are unique because of specifications and the specific technical parameters required for a given space application and because they have been developed to withstand the conditions and parameters of the highly ionized space environment. For a system to get to space, it first must endure the shock, vibrations, and forces of launch. Once in space, it is often subjected to rapid and continuous cycling between the extremes of heat and cold, to high internal temperature gradients, and to constant radiation and particle bombardment—especially that of atomic oxygen. Space assets are generally inaccessible for upgrade or maintenance and, thus, must be capable of operating reliably for their design life.

Emerging microtechnologies and nanotechnologies will not only provide size, weight, power, and thermal management benefits, but they also promise far greater functionality and higher operating speeds. Microelectromechanical systems (MEMS) and micro-optoelectro-mechanical systems (MOEMS) are experiencing tremendous growth. These technologies use optics, electronics, and mechanics in miniaturized space applications. According to a National Academy of Engineering (NAE) symposium report, MEMS and MOEMS technologies have opened many new opportunities for optics, electronics, and micropositioning equipment, especially as these pertain to space applications. For the first time, reliable microactuators and three-dimensional (3-D) optomechanical structures can be monolithically integrated with microoptical elements. MEMS and MOEMS technologies have made possible, for the first time, the integration of an entire optical table onto a single silicon chip. This capability translates to smaller, lighter, and more cost-effective space payload launches and will impact many space applications, including positioning, scanning, and telecommunications.

The inaccessibility of space and the cost of placing payloads into useful orbit dictate several additional considerations for space technologies. Miniaturization reduces the size and weight of the payload that must be boosted into orbit and reduces system power-consumption and heat-management requirements. Therefore, the motivation to reduce the size and power requirements of space assets is strong and has initiated many new microtechnologies and nanotechnologies (MEMS and MOEMS) specifically developed for space applications.

Quality assurance programs can test systems in the laboratory, and simulations can be used to improve the likelihood that the systems will perform properly after being placed in space. However, laboratory quality assurance testing must be conducted with caution since simulations of physical parameter effects must be performed in a concurrent fashion. For example, researchers now know that radiation exposure and atomic oxygen exposure are about 10 times more damaging (corrosively) when an item is exposed to them concurrently than when the same item is exposed to them separately. Materials must also be carefully selected to minimize out-gassing in space or to mitigate its impacts. Multifunctional structural elements that incorporate space-vehicle bus structure, operating functions and/or support functions will allow more functionality with less mass. All these “assurances” must be observed during the development of space technologies to ensure reliability. In addition, the development of reprogrammability and autonomy, which can provide self-governing or allow commanding from ground controllers, will allow space systems to be adapted to new or changing requirements.

In summary, each space technology development program or strategic plan—whether at NASA, the Services, or commercial firms—has specific goals. The four common goals include:

1. Reducing the cost of access to space and those space assets
2. Providing innovative technologies to enable ambitious future space missions and systems applications
3. Building capability in the U.S. space military/industry complex through collaborative and focused space technology development efforts
4. Sharing the results of these space technology efforts with the rest of the U.S. space community.

SECTION 19.1—SPACE AVIONICS AND AUTONOMY

Highlights

- Technologies in this section support navigation, attitude control, orbit determination, control of space vehicle dynamics, and other similar functions in space.
- Next-generation, space-qualified clocks will be several orders of magnitude more stable than those existing today. Candidates include ion trap, optically pumped, hydrogen maser, and next-generation rubidium and cesium technologies.
- Advances in space-vehicle autonomy and on-board processing capability are critical space-system enablers.
- Emerging technologies that enable autonomous operation of "clusters" of microsatellites or nanosatellites have exceptional leverage capability for unique applications. Use of Global Positioning System (GPS) and differential GPS and software for self-management of individual cluster elements to support cluster functions is included.
- Fault-tolerant computing and fault detection, isolation, and recovery technologies will be increasingly important as electronic feature sizes become smaller and processing speeds increase.
- MEMS will enable existing functions to be performed in smaller sized packages and entirely new categories of functions to be performed in space.

OVERVIEW

To perform their functions, space vehicles must navigate through space; orient their sensors, antennas, solar panels, and other systems properly; monitor and control their dynamics; and determine their orbits. For the most part, technologies to support these avionics functions in space systems are similar to those used in aircraft avionics. The space environment often requires that technologies be modified significantly from their airborne or terrestrial counterparts. One example is space-qualified atomic frequency standards (AFSs) or "clocks." While the basic reference atomic element and the quartz oscillator may be very similar to their terrestrial counterparts, the electronics control package and elements of the physics package for operation in zero gravity and stabilizing the internal environment are entirely different. Similarly, the space environment provides unique technology opportunities. For example, precisely determining absolute position in space by means of "star trackers," or gyro-astro trackers is possible because these trackers do not have to contend with distortion caused by the earth's atmosphere. The technologies that are unique for space are included in this section. See Section 16, *Positioning, Navigation, and Time*, for additional airborne and terrestrial technologies that can also be used in space.

LIST OF TECHNOLOGY DATA SHEETS
19.1. SPACE AVIONICS AND AUTONOMY

DATA SHEET 19.1. SPACE-QUALIFIED CLOCKS

Developing Critical Technology Parameter	Long-term stability better than 1×10^{-15} per day. The current terrestrial state of the art is slightly better than 1×10^{-14} per day. > 5-year service life for physics package; ability to remain dormant on orbit for > 2 years, yet turn on and stabilize rapidly on command. New physics packages to include new technology initiatives: ion traps and optically pumped units, reduced size/weight hydrogen maser, and next-generation cesium and rubidium technologies.
Critical Materials	High-quality quartz crystals; oscillator package; physics packages including rubidium cells; cesium tubes.
Unique Test, Production, Inspection Equipment	Fabrication techniques to achieve precise shape in critical physics package components; hand machining/tuning of many components; hand assembly and testing of each clock. Testing requirements are nontrivial.
Unique Software	Control algorithms require a deep, detailed understanding of all aspects of the performance of the clock physics package
Major Commercial Applications	Communications satellites, positioning and timing services that may compete with GPS [such as the European Union's (EU's) proposed public-private partnership Galileo system]; other space systems requiring precise on-board time information. Small overall commercial demand. International marine/maritime satellite (INMARSAT) may eventually incorporate clocks in some of its satellites.
Affordability	Current-generation rubidium and cesium clocks are $250K–400K each. Newer technologies will require additional development costs, and early models will likely cost more for increased capability. If hand machining and tuning can be eliminated in new technology clocks, unit costs should decrease.

BACKGROUND

For highest accuracy, atomic clocks are combined (i.e., double looped) with crystal local oscillators. Most of these clocks are passive devices that require the oscillator to generate a signal. The atomic process is servo-controlled to that source, which means that the crystal local oscillator dominates the short-term performance of the unit. In the case of cesium, the interrogation time of the beam tube leads to a crystal-dominated, high-noise output. Active hydrogen masers have very low short-term noise and do not require a crystal oscillator since they actively produce a signal. Because of the need to maintain a stable operating environment for the AFSs in space and to operate in the zero-gravity environment, many components and assemblies used in space-qualified AFSs are unique in comparison with the components and assemblies of their terrestrial counterparts. It is not only the environment, but also the low noise and tuned precision required in the control loop and modulation circuitry that make space-clock technologies unique. Special considerations for operation in space include:

- Thermal design to allow for operation in vacuum.
- Mechanical considerations to ensure survival in the launch environment.
- Use of radiation-hardened (rad-hard) parts in the electronics package to meet performance and lifetime requirements in the natural space radiation environment. Survivability requirements under given threat scenarios increase the level of specified radiation hardness.
- Extended lifetime and enhanced reliability requirements.

- Reduced size, weight, and/or power requirements.

Newer technology AFSs for use in space, specifically the ion traps and optically pumped designs, may be more similar to their terrestrial counterparts, may provide greater stability and/or smaller packages, and may be easier to build and maintain.

Terrestrial hydrogen maser technology is currently extremely heavy; however, if the mass can be reduced, space-qualified versions might lead to improved time accuracy and stability in space. Spacecraft versions under investigation range from adaptation of the large, full-cavity active maser to subcompact masers designed for GPS satellites.

DATA SHEET 19.1. GLOBAL POSITIONING SYSTEM–DIFFERENTIAL GPS (GPS–DGPS) USE IN SPACE

Developing Critical Technology Parameter	Absolute positioning of space vehicle to 1-cm accuracy; timing to 1-ns accuracy. Relative positioning of one space vehicle operating with other(s) within 1 mm; relative timing synchronization within 10 ps. Attitude control within 1 mm in three dimensions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	GPS/DGPS antenna/receiver calibration.
Unique Software	Real-time kinematic (RTK) and other error-reduction processing, in particular for DGPS-based relative positioning and timing among clusters of cooperatively operating, independent space vehicles.
Major Commercial Applications	Autonavigation of constellations of satellites for various purposes. Smaller satellites, with less space/weight needed for positioning and attitude control.
Affordability	This technology should reduce the cost of positioning and attitude control for small satellites and/or spacecraft in lower orbits.

BACKGROUND

Using GPS aboard a space vehicle can provide absolute and relative position and timing, or POSITIME, information to guide the vehicle itself or to guide it as an element of a cluster of cooperating vehicles. Using GPS in space can also reduce the workload of positioning, timing, synchronization, and attitude control systems aboard space vehicles and among space systems.

GPS technology is currently revolutionizing positioning, navigation, and time dissemination in airborne and terrestrial applications. It provides a worldwide position and time (or POSITIME) grid, which forms the basis for maps and for static and dynamic geographic information systems. It also reduces the need for carrying extra equipment when access to the GPS POSITIME information is available. GPS enables the coherent combination of information from multiple sensors and the sharing of information among cooperating weapon systems and platforms.

These same advantages can accrue for space-based systems, given access to GPS. NASA, the Services, and research universities are developing antenna technologies that will use GPS effectively in space. Incorporating GPS into space systems will reduce the weight because the GPS receiver will substitute for several traditional subsystems and will provide greater capability because GPS's POSITIME information will enable the integration of space platforms into the battlespace picture of terrestrial/airborne weapon systems.

DATA SHEET 19.1. SPACE CLUSTER NAVIGATION SOFTWARE

Developing Critical Technology Parameter	Relative positioning of one space vehicle operating with other(s) within 1 mm; relative timing synchronization within 10 ps. Attitude control within 1 mm in three dimensions. Management of more than 10 cluster elements in real time.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Self-managing, self-healing network software.
Major Commercial Applications	Autonavigation of clusters of satellites for various purposes.
Affordability	This technology should reduce the cost of space systems (e.g., large aperture sensors) that would normally require extremely large space vehicles.

BACKGROUND

Using GPS aboard a space vehicle can provide absolute and relative position and timing, or POSITIME, information to guide the vehicle itself or to guide it as an element of a cluster of cooperating vehicles. Using GPS in space can also reduce the workload of positioning, timing, synchronization, and attitude control systems aboard space vehicles and among space systems.

DATA SHEET 19.1. FAULT DETECTION, ISOLATION, AND RECOVERY (FDIR) AND TELEMETRY TRACKING AND CONTROLS (TT&C)

Developing Critical Technology Parameter	This developing technology area will provide the components and architecture for autonomous satellite health and status analysis and FDIR. Autonomous satellite operations will be the norm and will reduce the need for labor-intensive, human-directed satellite control functions. Artificial intelligence (AI) technologies are better incorporated on board to assess and report health and status when: • The spacecraft is functioning within nominal limits • The spacecraft is functioning outside nominal limits but can be autonomously reconfigured to a nominal state • The spacecraft is functioning outside nominal limits and requires human intervention to achieve a nominal state.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software to determine and define the autonomous parameters, based on current research in satellite anomaly resolution, with special emphasis on model-based reasoning technologies.
Major Commercial Applications	Reduced ground control infrastructure for commercial satellites; assistance in restoring functionality after space system failures.
Affordability	This technology should reduce the cost of ground infrastructure.

BACKGRUND

Satellite control by manual methods is expensive, error prone, and performance limiting. Currently, raw data are telemetered on a defined schedule to ground control stations, where human operators manually analyze these data to determine satellite health, status, and position. These operations then execute commands to maintain and control the satellite. Because most satellite maintenance and payload functions can now be automated, the current mode of operation wastes communications bandwidth (since large amounts of data are unnecessarily sent to ground stations), minimizes vehicle survivability and safety (since an anomaly will most likely not be discovered until its telemetry is delivered as scheduled), and wastes manpower resources (since human analysis of telemetry data is constantly required even though anomalies rarely occur). An evolutionary architecture and component set for automating satellite operations will migrate functionality from ground centers to space processors for implementing on-board autonomy while minimizing risk to the spacecraft. Hybridization of sensor data at the satellite level reduces the latency problems associated with manual methods. In effect, this changes the TT&C function from a process of continuous observation and control by human operators to one in which human operation is required only when exceptions occur.

Of utmost priority in an autonomous approach and methodology to space applications is the ability for the spacecraft to determine its own health and status accurately, safely, and consistently. Starting with components already developed under existing programs, this developing technology program will define a ground-based testbed for evaluating current research in satellite anomaly resolution, with special emphasis on model-based reasoning technologies. Also needed are innovative approaches to on-board data reduction and “data thinning” techniques that will capture a history of spacecraft parameter information as efficiently as possible. To reduce risk and provide immediate capability, this program should plan to integrate a testbed with a high-fidelity simulator that receives input from the space environment, from ground center personnel, and from the on-board command generator.

DATA SHEET 19.1. SOLID-STATE MICROELECTROMECHANICAL SYSTEMS (MEMS) NAVIGATION INSTRUMENTATION

Developing Critical Technology Parameter	MEMS technology has been used to develop gyroscopes and accelerometers for solid-state navigation systems (SSNSs). MEMS inertial guidance technology is needed for small, low-power reentry guidance systems for the Common Aero Vehicle (CAV) and reentry vehicles (RVs) that must survive extremely high g-loads. The technology could also be used to monitor and reduce low-frequency vibration in very large space structures. This technology development includes design, fabrication, and evaluation of cost-effective MEMS solid-state navigation instrumentation for insertion into systems to monitor relative motion. MEMS instruments must have at least the potential of 1 deg per hour gyro performance and 1 milli-g accelerometer performance and be able to maintain stability over many months.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Once this technology has been develop, many commercial space applications will benefit.
Affordability	This should be very cost effective and significantly reduce overall costs because of the small volume and power requirements of MEMS devices. The affordability aspects also enable use of these devices in nonnavigating applications.

BACKGROUND

Micromechanical device technology is the next logical step in the development of inertial measurement instruments. Current technology produces gyroscopes and accelerometers that are approximately 1-mm square. (One-degree-per-hour drift rates have already been reported in various research laboratories.) The dramatic rate of improvement has resulted because of the strong interest in terrestrial applications, including the development of sophisticated robots, toys, “smart” appliances, and personal navigation systems. Furthermore, the possibility of processing data from an array of microinstruments can enhance the accuracy of the data and makes possible the development of small, low-cost, highly redundant, accurate inertial measurement units (IMUs) adequate for the most demanding navigation mission.

SECTION 19.2—ELECTRONICS AND COMPUTERS

Highlights

- Unique, rad-hard, space-qualified very large-scale integrated (VLSI) technologies, components, and subsystems generally lag one or two generations behind their terrestrial commercial-off-the-shelf (COTS) counterparts.
- High-density interconnect device and high-speed data bus technologies for use in space are essential to realize the advantages of greater on-board processing in space.
- MEMS technologies will enable new space sensors and actuators with lower switching losses and greater sensing capabilities in space systems.
- Space-qualified broadband radio frequency (RF) devices, satellite laser communications technologies, quantum dots for radiation monitoring, and similar optical electronic devices will support increased space system capabilities and autonomy, requiring less extensive ground infrastructures for complex functions.
- Fault-tolerant computing technologies may enable the use of COTS systems in space, without bulky sets of redundant equipment.

OVERVIEW

This section covers discrete device and integrated circuit (IC) technologies, high-speed processing technologies, and emerging electronic technologies for space systems. The biggest differences between space-systems technologies and their terrestrial counterparts are radiation hardening, high-g survivability, and management of outgassing for space applications.

Because of the high costs and difficulties of getting payloads into space, space-bound electronics and computers need to be as light and small as possible. Similarly, power and thermal management concerns in space place a premium on energy-efficient technologies. Also, because of the inaccessibility of space and the forces of launch, these technologies must produce systems that are extremely reliable and rugged. Included are MEMS, MOEMS (see Section 19.4), analog and digital ICs, digital signal processors, and microminiaturized hybrid devices, which have been radiation hardened for space operations. Also included are rad-hard computer hardware, data buses, mass storage, and other computer components, plus unique software to accommodate the space environment.

Miniaturization allows current functions to be accomplished in smaller space-based components at less cost and allows the development of new functions based on new technologies or higher speed processing. Space vehicles that are reprogrammable from the ground while on orbit can be adapted over time for new or changing military missions.

LIST OF TECHNOLOGY DATA SHEETS
19.2. ELECTRONICS AND COMPUTERS

DATA SHEET 19.2. SPACE-QUALIFIED VERY LARGE-SCALE INTEGRATED (VLSI) TECHNOLOGIES

Developing Critical Technology Parameter	Total incident dose (TID) radiation hardness $> 5 \times 10^5$ rad (Si); prompt dose SEU $> 5 \times 10^8$ rads/sec; bit error rate (BER) $< 10^{-8}$ error/bit-day; latch up immune; minimum feature size over time targeted to track within a few generations of COTS VLSI, depending upon the application.
Critical Materials	Bulk silicon and silicon on insulation (SOI) wafers in diameters consistent with rad-hard foundry process.
Unique Test, Production, Inspection Equipment	Laboratory facilities with equipment such as Cobalt-60(Co-60) sources and low-power X-ray irradiators (ARACOR 4100); cyclotron facilities; and X-ray irradiation sources.
Unique Software	None.
Major Commercial Applications	Commercial satellites in low-earth orbit (LEO) and geosynchronous-earth orbit (GEO) orbits, particularly communications, imaging, and scientific applications.
Affordability	Smaller sized, more capable rad-hard VLSI devices will result in more performance for a given size/weight space system and will reduce system costs. Fully depreciated previous generation (larger feature sized) COTS silicon foundry equipment must be reused to minimize start-up costs for limited rad-hard demand.

BACKGROUND

To survive and operate within the radiation environment of space, the system electronics at the device, component, and subsystem levels must be designed to survive and operate over the system lifetime. For many radiation-intensive applications [e.g., deep space, strategic environments, medium-earth orbits (MEOs)], the electronics must be produced using silicon foundry processes and VLSI design techniques that are specifically designed for nonstandard rad-hard components but are not required when producing terrestrial commercial electronics. By using rad-hard devices and radiation-resistant design techniques, the system can ensure continued operation in natural and strategic space environments without extensive use of shielding or complicated redundancy approaches. Over time, design and process techniques employed in conjunction with shielding and overall system design allow the rad-hard process to track commercial process evolution, which has followed Moore's Law since the 1950s. To ensure effectiveness, the Radiation-hardened Electronics Industrial Base should maintain the capability to harden processes within a few generations of COTS technologies, depending upon the application. New generations of commercial VLSI processes are introduced at periods ranging from 2–3 years, which means equivalent-sized rad-hard generations generally lag COTS counterparts up to 4–6 years.

By maintaining a capability to produce electronics that can survive natural and strategic levels of space radiation and by using technologies that pace commercial VLSI processes, the design of military space systems can directly leverage exponentially increasing commercial electronics capabilities. The technical benefits are higher density electronics, lower cost per function, more processing power per unit mass, and more capability per watt. Over time, this translates into increasing payload and bus functionality, which will yield increased autonomy, decreased size, power, weight, and cost, and increased ability to perform sophisticated processing on orbit.

The market for rad-hard electronics components is much smaller by several orders of magnitude compared with the market for COTS components. Foundry tooling is a major cost element for VLSI fabrication. As feature sizes for COTS VLSI components decrease, new tooling is required. Fully capitalized (now excess) tooling from a previous-generation COTS foundry is becoming available to equip the next-generation rad-hard foundry.

DATA SHEET 19.2. SPACE-QUALIFIED VERY LARGE-SCALE INTEGRATED (VLSI) COMPONENTS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>TID radiation hardness > 5×10^5 rad (Si); prompt dose SEU > 5×10^8 rads/sec; BER $< 10^{-8}$ error/bit-day; latch-up immune.
<table>
<tr><th>Device</th><th>Parameter</th><th>> 5 yrs</th><th>> 10 yrs</th></tr>
<tr><td>ASIC</td><td>Gates/chip</td><td>20 Million (M)</td><td>50 M</td></tr>
<tr><td>ASIC</td><td>Clock speed</td><td>300 MHz</td><td>400 MHz</td></tr>
<tr><td>Static memory (CMOS)</td><td>Bits/chip</td><td>16 M</td><td>128 M</td></tr>
<tr><td>Microprocessor (GP)</td><td>Instructions/sec</td><td>300 M</td><td>600 M</td></tr>
<tr><td>FPGA</td><td>Gates/chip</td><td>1 M</td><td>4 M</td></tr>
<tr><td>A/D Converters (CMOS)</td><td>8 bit conv/sec</td><td>200 M</td><td>500 M</td></tr>
<tr><td>Nonvolatile Memory</td><td>Bits/chip</td><td>2 Billion (G)</td><td>8 G</td></tr>
<tr><td>DSP</td><td>Operation/sec</td><td>250 M</td><td>500 M</td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Bulk silicon and SOI wafers in diameters consistent with rad-hard foundry process.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Laboratory facilities with equipment such as Co-60 sources and low-power X-ray irradiators (ARACOR 4100); cyclotron facilities for protons; and X-ray irradiation sources.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>This technology will benefit all commercial satellites, particularly those in GEO and LEO orbits. High-value applications include narrowband (NB) and wideband (WB) communications and remote-sensing systems.</td></tr>
<tr><td>Affordability</td><td>Smaller sized, more capable rad-hard VLSI devices will result in more performance for a given size/weight space system and will reduce system costs. Fully depreciated previous generation (larger feature sized) COTS silicon foundry equipment must be reused to minimize start-up costs for limited radiation hardened demand.</td></tr>
</table>

BACKGROUND

As a companion to basic physical hardening of the silicon process to provide immunity to the effects of total dose [see Data Sheet 19.2, Space-Qualified Very Large-Scale Integrated (VLSI) Technologies], the design of physical devices for space must also keep pace with those offered in the commercial marketplace. In particular, each generation of reduced feature size in the commercial marketplace drives a revision in the design libraries used for radiation hardening of space electronic systems and the production of the basic circuits in the latest geometries. Not only must the process used to produce the devices be altered to enable the device to survive the effects of radiation damage over time, but the circuits must also be logically and physically designed to protect the devices against the effects of single-particle impingement (called single event upset, or SEU) on the silicon wafer. Design techniques must be applied to counter the effects SEUs and transients across the entire circuit.

DATA SHEET 19.2. SPACE-QUALIFIED SUBSYSTEM TECHNOLOGIES

<table>
<tr><td rowspan="7">Developing Critical Technology Parameter</td><td colspan="4">TID radiation hardness > 5×10^5 rad (Si); prompt dose SEU > 5×10^8 rads/sec; BER < 10^{-8} error/bit-day; latch-up immune.</td></tr>
<tr><td>Subsystem Area</td><td>Key Parameter</td><td>>5 yrs</td><td>> 10 yrs</td></tr>
<tr><td>Single CPUs</td><td>MIPS</td><td>300 M</td><td>600 M</td></tr>
<tr><td>Bus Bandwidth /IF Technology</td><td>Hz</td><td>100 M</td><td>400 M</td></tr>
<tr><td>Mass Storage Systems</td><td>Bytes</td><td>100 G</td><td>1 T</td></tr>
<tr><td>Power Converter Efficiency</td><td>Watts/Watt</td><td>90%</td><td>90%</td></tr>
<tr><td>Array Processors</td><td>Array size</td><td>16</td><td>256</td></tr>
<tr><td>Critical Materials</td><td colspan="4">Space-qualified VLSI components.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td colspan="4">Laboratory facilities with equipment such as Co-60 sources and low-power X-ray irradiators (ARACOR 4100); cyclotron facilities for protons; and X-ray irradiation sources.</td></tr>
<tr><td>Unique Software</td><td colspan="4">None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td colspan="4">Remote sensing; digital beamforming; circuit and channel switching.</td></tr>
<tr><td>Affordability</td><td colspan="4">Smaller sized, more capable rad-hard VLSI devices and space-qualified subsystems built with them will result in more performance for a given size/weight space system and will reduce system costs. Fully depreciated previous generation (larger feature sized) COTS silicon foundry equipment must be reused to minimize start-up costs for limited rad-hard demand.</td></tr>
</table>

BACKGROUND

Using devices described in other 19.2 data sheets [see Data Sheet 19.2, Space-Qualified Very Large-Scale Integrated (VLSI) Technologies, and Data Sheet 19.2, Space-Qualified Very Large-Scale Integrated (VLSI) Components], space-systems architects can design systems that elevate processing capability by orders of magnitude over current system capacities. The roadmap portrayed in this data sheet assumes that rad-hard electronics are available and that these electronics are within one to two generations of projected commercial terrestrial VLSI roadmaps, which envision capabilities to build subsystems that can store terabytes of data on orbit and access and process megabits/second of data in near-real time (NRT).

Mass storage systems could enable thousands of images to be accessed, correlated, and processed on orbit, thus avoiding congested communication links and time-consuming ground processing and data distribution.

Payload computing complexes can be constructed using supercomputing architectures to place more than 10^{10} floating point operations/second in space. This processing power will enable autonomous satellite operations and reduce or eliminate many computation-intensive ground systems.

DATA SHEET 19.2. HIGH-DENSITY INTERCONNECT

Developing Critical Technology Parameter	The technology requirement is for high-density space packaging technology to allow dense packaging of high-density VLSI, analog, MEMS, and other components while maintaining space-qualified temperature, thermal, and radiation performance. This developing technology includes high-density interconnects, space-qualified ball and column grid array technology, and special MEMS packaging systems for space applications requiring electrical switching components. Packaging technology for these systems will address hybrid analog, digital, and MEMS components that have to be packaged into compact structures suitable for spacecraft integration.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial space telecommunications and imaging applications.
Affordability	This technology effort will reduce costs through reduced mass, power, and volume and increase the efficiency of the electronic, switching, and connection components it will replace. High-density interconnect packaging will afford satellite systems the full benefits of MEMS integrated with other high-density electronics (i.e., small size and standardized, mass production, which means increased capability in space at lower cost).

BACKGROUND

This effort will include the development of MEMS packaging systems, high-density packing, column and grid array (CGA), and switching and active backplane components. Packaging technology for these systems will address the needs of many other applications, including integrated GPS/microgyro inertial navigation systems (INS) and microoptical systems.

The savings that this technology will provide include significantly reduced mass, power, and volume and increased system performance. Integrating sensors closely with the electronics eliminates layers of bulky, failure-prone packaging. Switches are the most prevalent of all electrical components. MEMS switches overcome the limitations of present solid-state switches because they have low losses, low cross talk, and high stand-off voltage; require power only for changing states; and eliminate biasing problems. Microswitches could be built into the packaging, thus eliminating any impact on the choice of electronic die. Densely packaged microswitches will enable the design of modular, fault-tolerant systems by allowing complete connect/disconnect of system components.

DATA SHEET 19.2. HIGH-SPEED DATA BUSES

Developing Critical Technology Parameter	Rad hard >1 mrad (Si); throughput > 8 Gbps for space-qualified systems; > 16 WDM. 128 WDM should be achievable.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Packet switching.
Major Commercial Applications	Commercial satellites, particularly meteorological, radar, imagery, mapping.
Affordability	Much development and testing have been completed, and connectors and other components are commercially available. Essential to leverage previous investment and monitor existing/planned government and industry advances to manage costs.

BACKGROUND

The satellite data bus provides a communication link between the processor, subsystems, and payloads. Fiber-optic data buses are essentially the electrooptical analogs of electronic data buses and can transmit even larger amounts of data by optical fibers than electronic data buses can transmit by electrical cables. Their high bandwidth capability can route data on board satellites at rates high enough to support sensor subsystems for many imaging applications. For example, a bus with a data rate of at least 800 Mbps is needed to support a relatively new sensor, the hyperspectral imaging system. Advantages of lower power, reduced size and weight, ease of integration, simplified grounding and connection requirements, and immunity to EMI make fiber-optic data buses desirable candidates for newer smaller, faster, economical satellite bus designs. The added flexibility of wavelength division multiplexing (WDM) has advantages over time division multiplexing (TDM) used in existing electronic digital system buses and could increase data rates further. Throughputs of 155 Mbps to several gigabytes per second are achievable.

The current standard, IEEE 1393, *Spaceborne Fiber-Optic Data Bus (SFODB),* was developed for real-time data-handling applications. It operates at 200 Mbps to 1 Gbps, with redundant ring architecture and up to 127 nodes. Four channels are combined to provide 4 Gbps on the downlink. It operates in a radiation environment of 100 krads (Si) with a 10^{-11} BER, which degrades to 10^{-9} BER during solar flares.

In the early 1990s, the U.S. Government funded most of the development work for fiber-optic data buses. Many of the components are commercially available today. [**Note:** *Most on-board communications networks for data transfer among different satellite subsystems use a MIL-STD 1553B advanced spaceborne computer modular (ASCM) wire-distributed data interface (WDDI) with peak transmission rates of up to only 100 Mbps.*] NASA has used fiber-optic data buses [following MIL-STD 1773 (1 Mbps) and a dual-rate bus (1 Mbps or 20 Mbps)] on several spacecraft, including the Hubble Space Telescope (HST), which was launched in 1990; the Solar Anomalous and Magnetoshperic Particle Explorer (SAMPEX), which was launched in 1992; the X-ray Timing Explorer (XTE), which was launched in 1995; the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched in 1997; the Earth Orbiter-1 (EO-1), which completed a ground demonstration in 1998; and the Microwave Anisotropy Probe (MAP), which is expected to be launched in fall 2001.

Throughout the world, most of the fiber-optic components used in the fiber-optic data buses are COTS components that have been developed by the optical communications industry. Possible exceptions would be the electronic application-specific integrated circuit (ASIC) chips for encoding and decoding the data on the optical signal, the exact design of the fiber optic cable, and the design of its associated connectors. Environmental factors that are driving these components include the relatively harsh radiation and extreme thermal conditions of space. Testing in the United States has demonstrated reliable performance up to 650 Mbps, with no bit errors. Potentially, this system could attain 12 Gbps using 12□asynchronous channels operating at 200 Mbps, which complies with SAE-AS4074,[1] *Linear Token Passing Multiple Data Bus*. This has been demonstrated in the laboratory and related components have flown in space.

The state-of-the-art speed for space-qualified systems is 1 to 2.5 Gbps for each optical link. Conventional WDM schemes can add several data streams to the same optical fiber bus with different wavelength channels. Faster optical communications speeds exist up to 8 Gbps, but the space qualification of the components is lagging behind. Currently, the number of waves that can be multiplexed is 8 or 16, but researchers believe that this number can eventually be increased to 128.

It is crucial to realize that, in general, no one device or technology can be discussed in isolation. A discussion of R&D in one area must involve mention of other devices and/or technologies, with the accompanying various applications. Switches, either routing or logic, control transmission speed and, therefore, are the primary bottleneck in a photonic system.

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[1] AS4074 is a Society of Automotive Engineers (SAE) standard.

DATA SHEET 19.2. MICROELECTROMECHANICAL SYSTEMS (MEMS) SPACE SENSORS AND ACTUATORS

Developing Critical Technology Parameter	This technology concerns the development of smart, lightweight, small, and inexpensive MEMS. It includes the development of microsensors, microelectronics, and microactuators and their integration into complete systems for use in space. This development will use silicon device microfabrication and micromachining technology to design, develop, and evaluate MEMS devices. The goal is to achieve component densities of 1,000 mechanical components per cubic centimeter with on-chip microelectronics of at least 10,000 transistors.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Many commercial applications will benefit once this technology is developed. MEMS accelerometers and INS fabricated from MEMS devices are leading terrestrial applications.
Affordability	Once developed, this technology should significantly reduce the overall cost of military space systems.

BACKGROUND

MEMS offer great promise in reducing the cost and increasing the capability, performance, and lifetime of future space systems. Launch-cost reduction will be the first result of incorporating MEMS into spacecraft. Current launch costs are on the order of $10,000/lb to LEO and will remain above $5,000/lb in the next generation of launch vehicles. Spacecraft incorporating MEMS will be much smaller and lighter, which will reduce launch costs. MEMS technology will also produce more-capable spacecraft. Microthrusters will allow smaller and more precise control maneuvers. Microsensors can be built into structures and components and will allow more precise monitoring of spacecraft health and status. Micromechanical components will allow redundancies for increased reliability and lifetime. Microelectronics will consume less power, thus reducing the demand on solar panels and batteries. On-board data storage and processing capabilities will be much greater, thus allowing greater autonomy and reduced ground support infrastructures and number of communications links.

There is a need for lightweight space MEMS components that have embedded sensors and actuators to perform various functions that now require large computer processors, sensor arrays, and, in many applications, ground control. MEMS technology will allow the integration of small, lightweight, low-cost, highly reliable mechanical components with electronic circuits, which will improve performance in several areas.

DATA SHEET 19.2. QUANTUM DOTS (QDs) FOR RADIATION MONITORING

Developing Critical Technology Parameter	The military Services need improved nonlinear optical materials for photonic devices, such as optical switches, which are critical elements in Navy optical communications and optical processing systems and radiation monitoring of space environments for personnel and equipment. The Navy and Air Force are in critical need of improved materials and new technologies for radiation dosimetry. In particular, all-optical, rapid read-out dosimetry technologies are needed to improve performance and reduce costs associated with both personnel and environmental monitoring. This technology development will include the following research efforts: • Fabricating novel materials using composite structures containing QDs to provide the Services with superior nonlinear optical materials for use in optical communications and optical processing • Developing superior QD materials and optically stimulated luminescence (OSL) parameters for radiation dosimetry applications such as personnel monitoring • Determining, characterizing, understanding, and then controlling the photophysical properties of doped and undoped QDs manufactured from semiconductors and metals. Current plans include developing improved synthetic methods for preparing impurity-doped nanocrystalline phosphors in silica matrices.
Critical Materials	Nanocrystalline phosphor glasses; highly transmissive phosphor glasses; thermoluminescent dosimetry (TLD); semiconductor doped glass.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	A potential dual use in QD optics is possible for a variety of applications: OSL nonlinear optics, remote sensing, optical switching, fast neutron dosimetry, and optical data storage.
Affordability	This should be an affordable technology to develop and will reduce costs significantly for future space applications in the areas of personnel and environmental monitoring.

BACKGROUND

Small particles of semiconductors or metals are chemically grown in plastics, glasses, or zeolites using techniques that include diffusive precipitation and chemical vapor deposition (CVD). Typically, a distribution of nearly uniformly sized particles results (e.g., 2.5±0.3 nm). Crystallites this small (1–40 nm) often show quantum size effects for electrons, holes, and/or excitons (i.e., when the bulk material deBroglie or Bohr radii are larger than the particle) and display different photophysical properties than the same materials in bulk. The optical and nonlinear optical properties of these composite materials will be investigated using a wide range of optical and laser spectroscopic techniques.

Significant progress has been made in understanding and exploiting the unique charge storage properties of the nanocrystalline phosphor glasses developed under this program. The nanocrystalline phosphors have the ability to trap electrons and holes and hold them stably for months. This phenomenon, combined with the excellent optical transparency of the phosphor glasses, has permitted a wide range of new applications based on the number of stored electrons and their effect on the index of refraction of the nanocrystalline-doped glass. For example, high-optical-quality, doped-glass phosphors have been developed and used as the storage media in demonstrations of volume holographic optical data storage. A single-mode KrF excimer laser was used to record holograms in 2-mm-thick samples of glass. Diffraction of He-Ne laser light was observed with an efficiency of 0.15 percent after just a few laser pulses. The photosensitivity of the phosphor glass is superior to other glasses previously studied. Significant progress is also reported in the development of nanocrystalline phosphor glasses for radiation dosimetry applications. The continued development of new glass phosphors for use in OSL dosimetry is of particular significance.

Novel doped-fused quartz phosphor glasses that demonstrate OSL sensitivity to 1 mrem and provide the ability to measure the absorbed dose several times for a given exposure have been developed. Femtosecond time-resolved laser spectroscopic studies of the nonresonant optical nonlinearity in nanocrystalline CuCl-doped borosilicate glass were completed and revealed an enhancement of the nonresonant optical nonlinearity above the 2-photon band edge. The magnitude of the nonlinearity was large (the nonlinear optical figure of merit was enhanced by 10) and the response time was unusually fast (< 30 fsec). For the program overall, 25 papers have been published, 18 patent disclosures have been filed, 10 U.S. patents have been issued, and 17 conference presentations have been presented.

DATA SHEET 19.2. FAULT-TOLERANT COMPUTING TECHNOLOGY

Developing Critical Technology Parameter	The objective of this technology area is to develop fault-tolerant computing approaches for the space environment. The primary technology challenge is incorporating COTS technologies into space-qualified systems while mitigating the effects of natural and strategic radiation environments The critical technology parameters are a function of the orbit, lifetime, availability, and performance requirements of the system under consideration. The goal is to survive and operate in natural and strategic radiation effects while continuing to meet mission objectives over expected mission lifetimes. Typical radiation characteristics for a 90-percent GEO application are: • TID radiation hardness: 100 K–200 krads (Si). • BER < 1^{-9} error/bit-day. • Latch-up immune.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Laboratory facilities with equipment such as Co-60 sources power-power X-ray irradiators (ARACOR 4100); cyclotron facilities such as Brookhaven and Berkeley for heavy ions and University of California at Davis for protons; and X-ray irradiation sources such as SNL and Maxwell.
Unique Software	Software must achieve fault detection, isolation, recovery, and system restoration without loss of data, at peak upset rates.
Major Commercial Applications	All commercial satellites.
Affordability	May enable more capability at lower operating cost if COTS electronics can be used. Tradeoff is higher nonrecurring cost of redundant equipment and/or fault-tolerant software development.

BACKGROUND

The development of fault-tolerant architectures sufficient to enable COTS electronics to operate in space will enable the use of current-generation commercial VLSI components and ASICs in military and commercial spacecraft. This allows spacecraft system architects to use technologies as they become available from the commercial electronic foundries rather than waiting for rad-hard versions (which typically lag by two technology generations). By doing so, spacecraft technologies could keep within one generation of the latest commercial device speeds, memory sizes, and clock rates so the spacecraft can operate at terrestrial state-of-the-art speeds, with corresponding power and weight advantages. Typically, clock rates and device densities double each generation, which would translate to a design advantage of 4:1 over spacecraft designed with intentionally rad-hard electronics. If achieved, this advantage would enable additional spacecraft functionality or could be applied to reduce spacecraft cost, weight, implementation schedule, and power use.

Fault-tolerant architectures must resolve multiple problems to achieve this advantaged capability:

- **Generational changes in the commercial VLSI processes introduce unpredictable and changing radiation characteristics in the electronic components.** Typically, radiation tolerance to total dose has been increasing, while susceptibility to SEUs has been decreasing. Future predictions indicate that these trends may continue for at least the next generation of electronics. However, solid predictions of commercial electronic performance in space radiation environments do not exist, and a continuous program of modeling and measurement is required to gauge this performance.

- **Fault-tolerant architectures typically use redundancy in achieving system goals.** This inherently incurs a penalty in power, weight, volume, system speed, and increased system complexity. These characteristics can substantially offset any advantage enabled by using strictly commercial electronic technology. Thus, the advanced fault-tolerant technology approaches are challenged to develop fault-tolerant approaches that retain the single string mass, power, weight, and clock-speed properties of rad-hard components.

DATA SHEET 19.2. BROADBAND RADIO FREQUENCY (RF) COMPONENT TECHNOLOGY

Developing Critical Technology Parameter	New and improved RF wave components, devices, and modules are required in the microwave/millimeter/submillimeter bands to support space-based radar (SBR), missile, communication, remote sensing, and (EW) electronic warfare. These circuits will need to be integrated into novel configurations and structures to achieve efficient, lightweight, compact, RF signal processors for receiver and transmitter applications. Particular emphasis must be placed on miniaturized monolithic integrated circuits (MMICs); low-noise amplifiers; efficient, high-power amplifiers; and frequency synthesizers. Specific requirements for space-based applications include radiation hardness for prompt effects (e.g., SEU) and for long-term degradation in the space environment. Experimentation and test and the physical modeling of active elements and circuitry are needed for the radiation environment.
Critical Materials	A wide range of semiconductor and semiconductor combinations and substrate, dielectric, and conductor materials are applicable.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial applications include satellite communications and remote-sensing satellites.
Affordability	This technology will reduce the costs of high-data-rate communications and signal processing in space. It will also enable new applications not now economically feasible.

DATA SHEET 19.2. SATELLITE LASER COMMUNICATIONS (LASERCOM)

Developing Critical Technology Parameter	Satellite LASERCOM is a line-of-sight (LOS), very high-data-rate, antijam, low-probability-of-intercept (LPI), lightweight communications technology. It is being developed primarily for use as satellite cross links but also for satellite downlinks and uplinks. This technology uses laser diodes for transmission, tracking, and alignment; low-noise avalanche photodiodes for collecting data transmissions; and charge-coupled device (CCD) arrays for tracking and alignment. This research includes advanced technology development of novel laser diodes that will address high bandwidth potential (> 10 Gbps) and other issues, such as improving laser output power, ensuring greater efficiency, and maximizing link availability.
Critical Materials	New and improved laser diode materials and the diodes themselves; receiver technology and materials for lightweight optics and lightweight, thermally stable structures.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	If this technology becomes available at low cost, many space-communication industry members would use it immediately for WB commercial satellite applications.
Affordability	This technology is expected to increase capabilities and reduce costs of satellite cross links once it has been operationally proven in space.

BACKGROUND

LASERCOM, a capabilities-based enhancement to communications systems, answers a need for high-data-rate communications. It also permits expansion of regional satellite communications coverage to global coverage via intersatellite cross links. High data rates support the transfer of imaging and mapping data. See Section 19.8, Sensors for Space Systems, for related space sensors and Section 19.12, Space-Based Lasers (SBLs), for space laser technologies.

SECTION 19.3—LAUNCH VEHICLES FOR SPACE SYSTEMS

Highlights

- Today's launch-vehicle technology includes mostly larger rockets, integration of solid and liquid fuel motors, multistage boosters, and advances in fuels and motor technologies.
- New payload-isolation technologies reduce vibration and acoustic loading during launch.
- Laser launch technology may allow economical insertion of microsatellites and nanosatellites into LEO.
- Throughout the world, there is a potential abundance of launch capability in traditional rocket boosters.

OVERVIEW

Today's launch-vehicle technology is essentially the incremental, evolutionary extension of the rocket technology of 50 years ago. Larger rockets, integration of solid and liquid fuel motors, multistage boosters, and advances in fuels and motor technologies highlight this technology. The data sheets discuss the innovative emerging technologies that focus, for example, on improvements in payload isolation from the stresses of launch. Vibroacoustic energy stresses account for nearly half of all first-day payload failures. Smaller sized and lighter weight microsatellites (approximately 100 kg) and nanosatellites (approximately 10 kg) will encourage the use of smaller boosters. One interesting technology for these applications is a laser Lightcraft, which is a laser-propelled trans-atmospheric vehicle (TAV). See Section 19.6, Propulsion for Space Systems, for propulsion technologies, including high-energy fuel and new motor technologies.

Launch vehicles are one of the most natural "dual-use" examples. All expendable launch vehicles designed for the military have been modified for commercial use. Placing a payload in orbit, whether military or commercial, requires essentially the same technology, and it is basically the same function. Vehicle preparation, payload integration, and launch-pad support systems are common between military and commercial operations. Next-generation EELV technologies are being developed specifically to take advantage of the synergy between military and commercial launch technology.

In the broadest sense, launch-vehicle technology involves avionics, launch operations, propulsion and fluid systems, materials and structures, production, and vehicle design and flight analysis. For the most part, this section focuses on launch operations. Nonspace technologies used for space or launch systems are covered in other sections. Launch-related space technologies are also discussed in Section 19.1, Space Avionics and Autonomy; Section 19.6, Propulsion for Space Systems; and Section 19.10, Structures for Space Systems.

LIST OF TECHNOLOGY DATA SHEETS
19.3. LAUNCH VEHICLES FOR SPACE SYSTEMS

DATA SHEET 19.3. ACOUSTIC DAMPENING MATERIALS TECHNOLOGY

Developing Critical Technology Parameter	This technology includes the development and demonstration of a 20 dB (10:1) decrease in acoustic disturbances in launch vehicle fairings using active/passive acoustic attenuation methods. The development includes innovative lightweight, low-cost acoustic damping and active attenuation for composite fairings for launch vehicles. Current acoustic attenuation is achieved by using custom sewn acoustic blankets, which are expensive, heavy, and decrease overall fairing volume. The goal is to improve on the existing methodology of using acoustic blankets and achieve an 80-percent lighter weight and a 50-percent lower cost.
Critical Materials	High “E” damping materials; lightweight composite materials for composite fairings; innovative lightweight, low-cost acoustic damping and active attenuation composites.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial payloads will benefit from this technology since currently all weight (mass) is a costly commodity to launch. In addition, current vibration conditions cause payloads to be lost or degraded significantly.
Affordability	This technology should provide more affordable launch systems. The increase in successful launches will significantly reduce overall program costs in the future.

BACKGROUND

Vibroacoustic energy accounts for nearly half of all first-day satellite failures. The systems most affected are solar arrays, antennas, tube amplifiers, and bearings/joints. Current acoustic attenuation is achieved by using custom-sewn acoustic blankets, which are expensive and heavy and decrease overall fairing volume. In addition, acoustic attenuation is primarily driven by the mass of the fairing. Since the mass of the fairing components is reduced significantly by using advanced composites, the acoustic disturbances within the fairing during launch will increase. This is particularly true in large launch vehicles, where low-frequency acoustic transmission is complicated by low-ring frequencies and low-frequency cavity modes (inversely related to cavity dimensions). Since blanket thickness and mass are inversely proportional to the frequency they must attenuate, low-frequency acoustics are especially difficult to control with traditional acoustic blankets. The payoff will be a factor-of-10 decrease in acoustic loading on the satellite. By decreasing acoustic loads on the secondary structure, the structural design requirements on solar arrays, antennae, and other components and systems will decrease.

DATA SHEET 19.3. LAUNCH VIBRATION ISOLATION SYSTEM (LVIS)

Developing Critical Technology Parameter	This is a technology development and demonstration program of an advanced LVIS capable of reducing the launch-induced structural borne vibrations at the satellite by a factor of 2 to 3. These systems will be designed to be passive and provide isolation in the axial, or lateral axis. LVIS will be a one-for-one replacement for the current payload adapter, with minimal increase in weight, volume, or power requirements.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial payloads will benefit from this technology since current vibration conditions cause payloads to be lost or degraded significantly.
Affordability	This technology should provide more affordable launch systems. The increase in successful launches will significantly reduce overall program costs in the future.

BACKGROUND

This is a technology development and demonstration program of an advanced LVIS capable of reducing the launch-induced structural borne vibrations at the satellite by a factor of 2 to 3. These systems will be designed to be passive and provide isolation in the axial, or lateral axis. LVIS will be a one-for-one replacement for the current payload adapter, with minimal increase in weight, volume, or power requirements.

DATA SHEET 19.3. LASER LAUNCH VEHICLES

Developing Critical Technology Parameter	The "Laser Lightcraft" is a laser-propelled, TAV, single-stage-to-orbit (SSTO) concept for launching small satellites into LEO. This novel launch system is envisioned to employ a ground-based laser (GBL) (megawatt-class) that would propel into orbit a 1-kg (dry mass), 1-m focal diameter laser Lightcraft, with a mass fraction of 0.5. The most promising tactical applications of this technology involve using GBLs, space-based lasers (SBLs), and the Lightcraft concept as a hypersonic kinetic kill vehicle (KKV). Such vehicles would be space, air, or ground launched depending upon the availability of laser energy. Although a first-stage chemical rocket might be required to accelerate the launcher to its top speed, the Lightcraft stage could then be used for sustaining velocity almost over any range because it would be completely air-breathing. Such vehicles would be able to sustain velocities in excess of Mach 6 as long as sufficient laser power was available.
Critical Materials	High-temperature, lightweight, composite ceramics are required to withstand and reflect the laser energy within the vehicle, which has 10,000 to 30,000 K plasmas and very high pressures created in the propulsion process. Coupon tests with carbon/carbon-based materials and shroud tests with graphite have shown poor results. Silicon carbide-based materials (Nicalon) have demonstrated better ability to withstand the laser blast up to 60 seconds and will be tested shortly as Lightcraft components
Unique Test, Production, Inspection Equipment	Remote, pulsed, high-power (> 100 kW), CO_2, electric discharge laser facilities in the Southwest are required for testing and future launches.
Unique Software	Guidance and control of the flight vehicle; pointing and tracking of the laser beam.
Major Commercial Applications	Amateur astronomy and radio; telecommunications; resources and weather surveys.
Affordability	High-power lasers for this technology could cost as much as $50M. The optical systems required for beam propagation to the Lightcraft may be of comparable cost. The vehicles are on the order of $1,000 per copy. Launch costs will be on the order of $500. No cost affordability study has been performed to date. Depending on the mass launch capability of this technology, it could provide very cost-effective launches in the future by reducing the cost of space transportation for small payloads to LEO (to less than a few hundred dollars per pound).

BACKGROUND

The Laser Lightcraft concept is being developed to reduce the cost of space transportation for small payloads to LEO (to less than a few hundred dollars per pound). For the price of electricity and a small maintenance cost, nanosatellites will be launched in large numbers from Continental United States (CONUS) sites—on demand and in any direction.

SECTION 19.4—SPACE OPTICS

Highlights

- Microoptics will begin replacing electronic components on chips, thus reducing heat and improving speed and throughput while reducing cost.
- Nanotechnology will improve electrooptics and nonlinear optics significantly, and this will have widespread military applications.
- Continued advances in optical coating material technologies will improve the hardness capability of military optics hardware.
- Lightweighting technology for space optics is vital to our future space requirements and will be addressed in two new technology applications.
- Software algorithms that determine and then compensate for deformations, or that purposely deform elements of space optics, are critical to obtaining and maintaining high resolution for space optics.
- Cooled space optics could support high-energy laser (HEL) space applications. Uncooled space optics could support space surveillance, reconnaissance, acquisition, tracking, and communications applications. Some space applications require temperature-stabilized optics.
- The microoptics and nanooptics that are being developed, especially in the MEMS and MOEMS components, will be a high visibility, exponentially growing technology area in the near future.
- Clusters of small satellites, each containing an element of a space optical system, are envisioned. These clusters could orbit together and collectively emulate much larger satellites than those that could be emulated if a single space vehicle were used. To provide the performance of much larger optics, small optical elements in each of these individual smaller space vehicles will be tied together by communications links and software.

OVERVIEW

Critical space optics technologies include the design of optical systems and components; specialized production methods, particularly for highly accurate, lightweight optical components; specialized, often exotic, materials used in these lightweight optics; and precision metrology associated with the fabrication and certification of space optics and in situ characterization of the surface during operations. Optics are characterized as cooled or uncooled. Some space optics technologies are unique because of the demanding space environment. In particular, these delicate optical systems must endure up to 20-g launch loads, greater than 120-dB vibration, on-orbit contamination by out-gassing of various satellite components and systems, atomic oxygen within the space environment, and degradation caused by particle impacts in space.

Size and weight are major considerations in any space launch. Power consumption and heat loads are additional considerations when on orbit. Low-power, relatively large optical elements are required for space power, relay, and communications systems. Optical elements are currently limited in size by space booster payload fairings. Optics, larger than those that can be boosted into space by such launch-vehicle limitations, must be assembled in space (either from separate pieces or by unfolding elements), or the optics must be manufactured in space. In-space manufacturing or construction technologies remain critical, particularly for applications that require exceptionally large, fragile membrane or very lightweight optics (too large and/or too fragile for launch stresses). Technologies for unfolding or assembling large optics and for obtaining and maintaining proper shape and finish in the process also remain critical. Software algorithms that determine and then compensate for deformations or that purposely deform elements in space optics are critical for obtaining and maintaining high resolution for space optics.

As advances in microsatellite and nanosatellite development continue (aided by advances in space-based computing power and techniques for space-vehicle autonomy and self-management of clusters of these small satellites), a new category of space optics will emerge based on these software and hardware technologies and techniques. These systems will include clusters of microsatellites/nanosatellites that could orbit together and collectively emulate much larger satellites than those that could be emulated if a single space vehicle were used. To provide the performance of much larger optics, small optical elements in each of these individual smaller space vehicles will be tied together by communications links and software.

As the use of optics in space has increased, changes have become necessary in the design, manufacturing, and process controls of these new technologies to provide affordable, lightweight, rugged, and highly reliable systems. Many new MEMS and MOEMS applications incorporating lasers have spawned numerous designs for reducing the weight and size of space electronics.

The use of commercial space optics technologies is important in the overall affordability of the space component or system. Many satellite payloads are planning on using microoptic technologies in the form of MEMS and MOEMS for surveillance illumination sources employed with special imaging applications.

LIST OF TECHNOLOGY DATA SHEETS
19.4. SPACE OPTICS

Technology Name **Page**

DATA SHEET 19.4. LARGE SPACE OPTICS AND COATINGS

Developing Critical Technology Parameter	Space applications require large, extremely lightweight mirrors that have diameters in the 4-to 100-m range and F numbers in the 1.5 to 2.5 range. A fast focal ratio is needed for compact, lightweight space optics that have the light-gathering power and resolution required to meet current military requirements, which include fractional wavelength tolerances. Thin glass shells attached to actuators on a lightweight rigid support structure constitute the current developing technology. Alternate technologies are also being addressed and include thin plastic, mylar, and/or metal-foil-stretched membranes. Using many smaller flat surfaces to form a primary optic configuration may be an acceptable technology to meet this requirement. The technology will require hundreds to thousands of square-meter surface for some applications. All these large-optics technologies are currently being investigated at a low developmental level. New coating designs will be developed and demonstrated for large optics. A prime candidate mirror coating is one called “Perfect” mirror, designed by MIT. Preliminary coating designs indicate that this mirror design will have the highest reflectivity, can be applied inexpensively, and is flexible enough to be folded or rolled for deployment in space. This design and application will be investigated and evaluated during this effort. Current surface densities of 25 to 40 kg/m^2 have been demonstrated, but the need is for 5- to 15-kg/m^2 surface density mirrors for midterm space applications and as low as 1-to 5-kg/m^2 surface density for longer term, larger aperture optics applications.
Critical Materials	Thin stretchable membranes that can maintain an optical figure and high reflection while surviving the space environment; fast, high-resolution spatial modulator material that will remain stable in a space environment.
Unique Test, Production, Inspection Equipment	Test procedures for aligning multiple optical surfaces in the remote space environment; micropositioning “smart structures” for the fine tuning of these components.
Unique Software	None identified.
Major Commercial Applications	This technology will enable space surveillance for astronomical observations and ground surveillance for crop, weather, and mapping purposes. In addition, there is interest in using these reflectors for visible-to-RF space communications between satellites and from earth to satellites.
Affordability	This technology will produce large optics at significant weight reduction and smaller folded size for launch to allow more affordable launches of large imaging and relay satellites.

BACKGROUND

Inflatable or membrane mirrors, in addition to their established value for RF systems, are a potential revolution in optical imaging systems. Accuracy requirements for optical systems, even with adaptive optics, are probably two orders of magnitude more restrictive than the accuracy requirements for RF systems, but optical apertures do not require as large a diameter as RF systems do for the same resolution. This new, developing membrane mirror technology is essential for apertures larger than the 2.4-m HST, which is made from a single honeycombed glass substrate with a surface density of over 250 kg/m^2. Many current space observation requirements dictate that optics in the 5- to 8-m diameter range are needed now, and up to 100-m diameters will be required for mid-term space applications.

For large space optics, large and extremely uniform membranes have to be manufactured. The membranes must be mounted on a frame that deploys to extremely accurate tolerances on orbit, and the mounting frame and the membrane will require active control to suppress disturbances, including real-time correction of residual wavefront errors. This development work is heavily leveraged by past, present, and planned work in inflatable structures for other applications, smart structures, and stable structures. The end result will be a subscale demonstration of a smart structure for mounting and deploying a membrane mirror. The time-varying performance of the system (in conjunction with appropriate adaptive optics developed) will be demonstrated by imaging an artificial scene. The end product of this research will be a viable membrane optical system weighing anywhere from 35 percent to 5 percent of current system weight, with an extremely low "mirror" fabrication cost. The light weighting of the structure and the initial reduced size of the folded membrane will allow more affordable launches of large optical imaging and relay satellites.

DATA SHEET 19.4. COOLED TRANSMISSIVE OPTICS

Developing Critical Technology Parameter	This technology development effort will determine the technologies required for manufacturing cooled transmissive optics, such as beamsplitters and windows required for HEL space systems. Significant performance improvement should result in decreased distortion caused by the thermal heating of uncooled transmissive optical elements. Currently, no technology is available for the active liquid cooling of transmissive optics similar to that currently used for reflective optics. The prebonding contamination problem was solved for small optics using optical contact by perfecting a method of swabbing away contaminants. "Frit" bonding technology will also be investigated to determine possibilities and parameter matches for this approach.
Critical Materials	Bonding compounds for transmissive optical elements in the visible and IR spectrum. These compounds must have low absorption in the wavelength region of interest and be nearly the same index of refraction as the host material.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	No significant application in the commercial regime is known. This technology is primarily for HEL surveillance and weapons applications.
Affordability	Costs of new coolant will be offset by reduced costs of storing/using the large inventory of hazardous carbon tetrachloride.

DATA SHEET 19.4. PHOTONICS FOR SPACE APPLICATIONS

Developing Critical Technology Parameter	Efficient, lightweight, reliable, rad-hard photonic components are needed for a variety of space-based applications, including optical communications, phased array antennas, and sensors. Critical components include efficiently pumped high-power fiber and semiconductor amplifiers, low-drive voltage modulators, low-loss fiber-optic splitters and WDM combiners, and fast optical switches and filters. Polarization-insensitive components are also desirable. Other useful components/devices include all-optical analog-to-digital (A/D) converters for high-bandwidth on-board processing and storage.
Critical Materials	Rare-earth doped materials, nonlinear optical materials such as potassium titanyl phosphate (KTP), electrooptic materials, and polymers.
Unique Test, Production, Inspection Equipment	Components must pass temperature-cycling, thermal-vacuum, and radiation tests.
Unique Software	None identified.
Major Commercial Applications	Photonic components are used extensively throughout the telecommunications industry. So far, these components have been developed with terrestrial applications in mind. Space has a unique set of requirements that are not met by terrestrial products.
Affordability	Component qualification for space is more stressing and costly than qualification for terrestrial applications. Inexpensive components would reduce costs and enable more extensive testing.

BACKGROUND

Photonic components will be used in future space-based systems and will offer improved capabilities over traditional RF components in the areas of communications and system control. Before photonic components can be implemented into space platforms, they must be reliable and efficient. Significant reductions in power consumption and/or increased power output from photonic components can enable missions where power and storage space are a premium. Reliability is always an important issue since typical mission lifetimes will range from 7–15 years. Component R&D directed toward space applications is essential because COTS technology is unlikely to satisfy the requirements of space-based systems.

DATA SHEET 19.4. MICROPHOTONIC TECHNOLOGY

Developing Critical Technology Parameter	This technology effort will develop and demonstrate prototype microphotonic devices for space applications. It is required for the integrated photonics used for control of microwave phased-array antennas and other space optical components. Significantly improved microphotonic components will result in fiber-optic gyros that occupy a smaller volume and have lower power consumption at lower cost but greater rotational rate sensing capability than presently available. Developments in this research effort will also contribute to improved performance of phased-array antennas through optoelectronic control and the enhancement of optoelectronic processors.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology will play a significant role in commercial space telecommunications satellites.
Affordability	This technology should make the components and systems very affordable.

BACKGROUND

Improved microphotonic components will result in fiber-optic gyros that occupy a smaller volume and have lower power consumption at lower cost but a greater rotational rate sensing capability than presently available for space applications.

DATA SHEET 19.4. MICRO-OPTOELECTRO-MECHANICAL SYSTEMS (MOEMS) ELECTRONICS FOR SPACE OPTICS

Developing Critical Technology Parameter	The requirement for MOEMS is growing. This technology research will develop simple, low-power analog-control electronics for continuously positioned micromirrors and for an optical wavefront phase aberration detection and correction system. Initial field test devices will incorporate space-based attitude sensors. Micromirrors coupled with analog control electronics are required to enable the extremely small, low-power adaptive optic systems planned for space systems. This technology will permit a space sensor system to compensate for changes caused by mechanical shock, thermal cycling, or misalignment of the optics and would even permit the use of low cost, lightweight optics because the mirror surface corrects for aberrations not corrected by the low-cost optics/lenses.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms need to be developed to support the analog electronic controls for high-speed positioning.
Major Commercial Applications	Commercial applications include high-speed printing and advanced processing techniques involving phase error correction for advanced imaging systems, such as high-resolution space surveillance of crop diseases.
Affordability	This technology should yield lower cost, higher capability optical systems for space.

BACKGROUND

Advantages of this developing technology include better focus control for more efficient sensors and advanced processing techniques involving phase error detection of extended objects, thus eliminating the need for artificial point sources such as laser guide stars.

Major applications include the reduction of atmospherically induced and systematic aberrations for ground-based telescopes and for satellite-based optical imaging and tracking sensors. This technology development supports the following:

- Real-time image compensation
- Intelligent optical components
- Multifunction electrooptical systems for target detection and identification
- Deployable optics
- Low-cost star sensors
- Increased signal collection efficiency of electrooptical sensors
- Precision optics
- Precision attitude determination
- Low-light acquisition
- Tracking and imaging
- Adaptive optics and beacon sensing.

Micromirrors, coupled with analog control electronics, will enable extremely small, low-power adaptive optic systems. Adaptive optics can correct errors within the optical system. This permits a system to compensate for changes caused by mechanical shock, thermal cycling, or misalignment of the optics and would even permit the use of low-cost, lightweight optics because the mirror surface corrects for aberrations not corrected by the low-cost lenses.

Optical components will also apply to other imaging and attitude sensors. Novel, extended-object phase-detection techniques will be tested. The result of these efforts will be a toolbox of adaptive optics components, processors, and system designs that can then be applied to specific sensor needs, such as star trackers, imaging optics, or other micromachined earth/sun/star attitude sensors. Complete systems will be packaged in high-density multichip modules.

SECTION 19.5—POWER AND THERMAL MANAGEMENT

Highlights

- The key features of power sources for space systems are efficiency, light weight, long-duration, and reliability. Future space applications require high power—more than 10 kW—for more than 10-years' duration.
- The preference is passive systems, which operate maintenance free, provide heat rejection by radiation, require low mass and volume, and are capable of reliable autonomous operation.
- Mechanically pumped thermal systems are more complicated but provide greater heat rejection potential.
- New multiband gap solar cell technologies can increase output power conversion efficiencies, theoretically up to the 40–42 percent range.
- New structural technologies enable rollable, lightweight, flexible solar arrays.
- Two key energy-storage technologies include lightweight, high-efficiency batteries and flywheels.
- Adaptation of current terrestrial batteries—in particular, lithium-ion technology—to space systems requires increasing cycle life significantly.
- Efficient flywheel system technologies provide increased deep-discharge cycle life and potential additional functionality as part of space vehicles' momentum systems.

OVERVIEW

The key features of power sources for space systems are efficiency, light weight, long duration, and reliability. Space applications require high power—more than 10 kW—for more than 10-years' duration. The preference for space systems is passive systems, which operate maintenance free, provide heat rejection by radiation, require low mass and volume, and are capable of reliable autonomous operation. The prevalent source of space power is solar, and new technologies are directed at reducing their mass and increasing their efficiency. Energy-storage devices account for a large percentage of the space-vehicle power systems and space and weight. New battery and mechanical technologies are directed toward reducing mass, increasing efficiency, and providing additional functionality. Other technologies address efficient heat removal.

Power and thermal management technologies are mandatory for the effective use of the space environment. Space applications require high power levels and long-duration operation at controlled operating temperatures. Solar cells mounted on the surface of spacecraft, perhaps even incorporated into the actual structural elements or panels or deployed on solar arrays, are highly reliable. Silicon arrays with 14-percent efficiency are common. More radiation-resistant, gallium-arsenide arrays yield efficiencies up to 19 percent. Advanced technologies, in particular multi-band-gap solar cells, should lower costs, increase efficiency, and provide higher radiation resistance. Two-junction, InGaP/GaAs solar cells yield efficiencies up to 29.5 percent; three- and four-junction cells have theoretical efficiencies approaching 42 percent. Current state of the art in the commercial market is 26-percent efficiency, with expectations to achieve 30-percent efficiency within a few years.

Current state-of-the-art solar arrays use rigid honeycomb substrates to provide launch stowage and deployed structural support of crystaline silicon and single- and multi-junction GaAs cells. These substrates have reached practical limits in thickness and densities, effectively limiting the power output to 50–80 W/kg from these cell technologies. New shape memory alloy (SMA) devices, ultralight composites, thin-film photovoltaics, and rollable membranes may provide solar arrays up to 5 times lighter than current technology, opening the way for power outputs up to 150 W/kg.

Energy-storage-device technologies include batteries and mechanical storage devices (e.g., flywheels). Current space-battery technologies include nickel-hydrogen and nickel-cadmium. Long life, deep discharge, and high reliability are required in space systems. Terrestrial applications have recently switched to lithium-ion batteries, but this technology demonstrates limited cycle life. Technologies that extend these batteries' lives to more than 30,000 cycles should enable their use in space systems and will result in reductions in the cost and weight of space power storage systems.

Emerging solar array technologies should enable a new generation of ultralight arrays that provide specific power at 150 W/kg or greater. Technologies supporting this capability level are thin-film copper indium diselenide (CIS) photovoltaic cells produced in continuous sheet form, high stiffness composite support structures, and SMA devices for efficient deployment actuation.

Mechanical storage systems involve flywheel technologies. Use of these technologies in space systems is attractive because they support deep-discharge cycles over lifetimes that are 10 times those of batteries. They also provide multiple functions, potentially serving in the momentum management function of space systems. Critical technologies include high-speed carbon composite rotors, vacuum containers, magnetic bearings, high-energy containment spin tanks, brushless DC motors, and momentum-management software.

Thermal management on spacecraft will increasingly become a controlling factor in many applications. Heat rejection may become a barrier to increased capabilities and functionality in space systems. Passive systems, capillary heat pumps, and mechanically pumped loops compose the technology migration path.

LIST OF TECHNOLOGY DATA SHEETS
19.5. POWER AND THERMAL MANAGEMENT

DATA SHEET 19.5. ULTRALIGHTWEIGHT FLEXIBLE SOLAR PANELS

Developing Critical Technology Parameter	Emerging solar array technologies should enable a new generation of ultralight arrays that provide specific power at 150 W/kg or greater. Technologies supporting that capability level are thin-film CIS photovoltaic cells produced in continuous sheet form, high stiffness composite support structures, and SMA devices for efficient deployment actuation.
Critical Materials	High-efficiency photovoltaics that can be developed in thin-film form for space environments; improved CIS photovoltaics.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Many commercial satellites firms will use this technology once the system-level issues are accommodated.
Affordability	This technology will enable a substantial cost reduction. The process for manufacturing thin-film solar cells in sheet form costs much less than the current practice of manufacturing individual cells and then electrically interconnecting them and bonding them onto a substrate.

BACKGROUND

Conventional state of practice and current state-of-the-art solar arrays use rigid honeycomb substrates to provide the launch stowage and deployed structural support of rigid crystalline silicon and single- and multijunction GaAs cells. Rigid-panel composite face sheet thickness [~ 0.010 in. and honeycomb densities (1.6 kg/m^3)] have reached the practical producible limits, limiting rigid panel solar array technology to a specific power of ~50–80 W/kg, depending on the specific cell type used.

Revolutionary solar array approaches that can meet the ambitious DoD and NASA specific power (>150W/kg), packaging (300 W/m^2), and stowage (< 0.15 m^3 for a 750-W array) targets are becoming feasible. Recent advances in SMA devices, ultralight composites, and thin-film CIS photovoltaics have shown potential in providing low-cost solar array systems that are a factor of five lighter than the current state of the practice and a factor of three lighter than the current state of the art. Meeting these performance targets would enable significant improvements in spacecraft payload fraction, cost, life, and/or performance as traded at the system level for each mission.

These technologies may result in a rollable membrane solar panel. A program is underway that will investigate innovative and efficient solar array deployment schemes that use SMA-actuated flexures and mechanisms, thin-film CIS photovoltaics, and high stiffness and lightweight composite frame structures that can meet the challenging power goal of > 150 W/kg. This technology program will investigate innovative and efficient solar array deployment schemes required for future spacecraft. The synergistic merging of the SMA and lightweight structures technologies into an advanced lightweight solar array can meet the requirements of the now-emerging generation of small satellites. This effort will result in improved cost, weight, risk, reliability, and power.

DATA SHEET 19.5. HIGH-EFFICIENCY SOLAR CELLS

Developing Critical Technology Parameter	Solar cells employing three and four junctions are in development to provide the next major step in conversion efficiency beyond the dual-junction cells that are entering routine space flight status. The theoretical efficiency of four-junction cells reaches about 42 percent, but the required current matching between the stacked junctions and manufacturing practicalities will prevent reaching that level. The four-junction approach will require the application of new materials and advanced solar cell production processes. A practical goal for conversion efficiency of 4-junction solar cells at the end-of-life (EOL) point for typical space missions is 35–37 percent for a target launch date of 2005.
Critical Materials	Candidate materials identified are as follows: InGaAlP, GaAs, InGaAsN, (In(GaAl)AsN), InGaP/GaAs, InGaP/GaAs/Ge, and ZnGeAs.
Unique Test, Production, Inspection Equipment	Metallo-organic chemical vapor deposition (MOCVD) processing of many layers and a multitude of screens make for a very difficult process.
Unique Software	None identified.
Major Commercial Applications	High-efficiency solar cells have tremendous leverage for space power systems for all commercial applications. Increased solar cell efficiencies reduce satellite mass and launch cost and may increase satellite mission lifetime.
Affordability	This technology should be very affordable since the additional junctions yield an increment in efficiency that typically far exceeds the increment in cost.

BACKGROUND

Since the early 1960s, the paramount goal of the solar cell community has been to improve the optical-to-electrical energy conversion efficiency of solar cells. The size, mass, and cost of conventional satellite space power systems depends strongly and directly on this efficiency. A high solar cell energy conversion efficiency is desired to reduce the area of a solar cell array, thereby enabling a greater payload mass and reduced launch vehicle costs. For example, an EOL electrical power requirement for a typical geosynchronous communications satellite might be 10 kW or more. Since the air-mass-zero (AM0) solar energy flux in space is 1.353 kW-m^{-2}, the 10-kW electrical power requirement would require a solar array panel area of about 50 m^2 when using 20-percent efficient solar cells. However, by increasing the solar cell efficiency to 40 percent, the same 10-kW electrical power requirement could be met with a solar array panel of one-half the area and weight. Achieving such high efficiencies requires the use of multijunction cells.

Progress toward the development of multijunction solar cells was first reported in the 1980s. In 1994, a two-junction InGaP/GaAs solar cell was disclosed, with an energy conversion efficiency of 29.5 percent for incident light from the sun at 45° above the horizon (denoted as AM1.5).[2] In 1996, a 3-junction InGaP/GaAs/Ge solar cell was disclosed, with an AM0 (space solar spectrum) energy conversion efficiency of 25.7 percent.[3]

High efficiency three- or four-junction solar cells are being developed. These cells can achieve a theoretical AM0 energy conversion efficiency of about 40 percent. This technology will exploit InGaAsN, GaAs, and InGaAlP as candidate materials. The bandgap energy of the InGaAlP third homojunction is higher than that for an InGaP homojunction in a conventional multijunction solar cell. This increased bandgap energy of the third homojunction,

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[2] K.A. Bertness et al., “29.5% Efficient GaInP/GaAs Tandem Solar Cells,” *Applied Physics Letters*, Vol. 65, pp. 989–991, 1994.

[3] P.K. Chiang et al., “Experimental Results of GaInP$_2$/GaAs/Ge Triple Junction Cell Development for Space Power Systems,” *Proceedings of the 25th IEEE Photovoltaic Specialists Conference*, pp. 183–186, 1996

in combination with the provision of the InGaAsN first homojunction, increases an overall energy conversion efficiency for the solar cell of this cell as compared with conventional multijunction solar cells.

The bandgap energies for each p-n junction are tailored to provide substantially equal short-circuit currents for each p-n junction, thereby eliminating current bottlenecks and improving the overall energy conversion efficiency of the solar cell. In addition, using an InGaAsN p-n junction overcomes super-bandgap energy losses that are present in conventional multijunction solar cells. The high efficiency three- or four-junction solar cells can be fabricated by MOCVD. Theoretical calculations for the four-junction high-efficiency solar cell show an overall AM0 energy conversion efficiency of 42.3 percent.

DATA SHEET 19.5. HIGH-CYCLE-LIFE LITHIUM-ION BATTERIES

Developing Critical Technology Parameter	Use of lithium-ion batteries is emerging in space applications, but these batteries are still limited in their total cycle life capability at high levels of use or deep depth-of-discharge. Demonstrated cycle life is sufficient to support geosynchronous missions but is not yet competitive for full penetration of LEO applications where the batteries are cycled at least once a day and typically every revolution of the spacecraft. The target-competitive cycle life and use for LEO applications is 30,000 cycles at 40 percent or greater depth-of-discharge. At this level, lithium-ion technology will outperform nickel-hydrogen batteries. Continuing technology development is expected to increase significantly the cycle life of lithium ion batteries. Key mechanisms that cause loss of reversible capacity can be mitigated via properly selected additives that can be incorporated into the electrode/solid electrolyte composites.
Critical Materials	Specific materials determined to be the most effective in mitigating capacity degradation will be critical for achieving the targeted cycle life and depth-of-discharge combination.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Long-life lithium-ion batteries would definitely benefit commercial space missions. They may also find applications in various commercial markets that currently use lithium-ion batteries and those that use other battery technologies because of current lithium-ion life limitations.
Affordability	This technology will have a significant effect in reducing the overall cost of spacecraft batteries.

BACKGROUND

On most spacecraft, the battery system is one of the heaviest and costliest components. The current space-battery technologies are nickel-hydrogen and nickel-cadmium. These systems have the inherent life capability necessary for space missions. Their life capability as a function of depth-of-discharge is sufficiently well known to enable high-confidence designs.

Terrestrial applications have undergone a mass switchover from nickel-cadmium to nickel-metal-hydride and recently to lithium-ion batteries. Lithium-ion batteries provide substantial mass and cost advantages and reasonable lifetimes. However, their overall life capability has not reached a point where LEO missions could be undertaken confidently.

Lithium-ion battery improvements that enable much greater life, possibly at somewhat increased cost, have been proposed. While the economics of terrestrial mass markets may not favor these improvements, they could be pursued specifically for space. Achieving an increased cycle life would have tremendous leverage for space missions. It would increase the spacecraft mass fraction available for payloads and reduce overall system costs.

DATA SHEET 19.5. ENERGY STORAGE FLYWHEELS (ESFs)

Developing Critical Technology Parameter	ESFs efficiently use electrical energy, store it as kinetic energy, and return it as electrical energy when discharged. The kinetic energy is typically stored in high-speed carbon composite rotors suspended in a vacuum container on magnetic bearings. A brushless DC motor/generator serves to transform energy between electrical energy and kinetic energy. Benefits include improving specific energy over chemical batteries, supporting repeated deep-discharge cycles, and providing maintenance-free service, with a lifetime often exceeding chemical batteries by a factor of 10 for many applications. Unlike chemical batteries, ESF technology is unaffected by ambient temperature. Early applications for ESFs will include high power, short-to-moderate ride time, uninterruptible power systems (UPSs), and similar applications such as airborne radar and laser applications. Satellite application is attractive because of the mass savings and the ability to combine the functions of energy storage and momentum management into a single long-life device, thus reducing parts count and improving reliability. Other military applications could include using an ESF with a renewable energy source (solar or wind) as a remote low-service power station or combining it with a fuel cell for a low observable (LO) power source. The critical technology parameter for ESF spacecraft application is specific energy. A specific energy goal of 66 Whr/kg is proposed, which includes the controlling electronics and incorporates the momentum management function.
Critical Materials	High-tensile-strength carbon composite fiber.
Unique Test, Production, Inspection Equipment	High-energy containment flywheel rotor spin tank.
Unique Software	Adaptive state-space control algorithms for active magnetic bearings.
Major Commercial Applications	Electric utility applications including UPSs, load leveling, diurnal peak shaving, and distributed on-grid energy storage. Other applications will include renewable energy-source power systems, commercial satellites, and electric vehicles of various types, including trucks, buses, trains, and automobiles.
Affordability	Initial ESF costing for spacecraft application is comparable to the cost of the equipment it replaces (chemical battery, reaction wheel, and control electronics). In production quantities, a similar relationship is expected for terrestrial applications that use long-life chemical batteries with charge control/interface electronics.

BACKGROUND

Commercialization of ESFs for UPS applications has begun. Early designs are commercially available with improved performance units in development or beta testing.

The simultaneous use of ESF for energy storage and for momentum management makes ESF a unique high-leverage application for spacecraft. While ESF is currently a development item for satellites, it benefits satellite missions by increasing the payload mass fraction, improving electrical efficiency, reducing platform jitter, and improving reliability. The reduction in platform jitter over a conventional momentum control wheel is achieved by suspending the ESF rotor on a magnetic bearing. The magnetic suspension provides excellent isolation of the mount from the rotating assembly (between –40 to –70 dB) when compared with the vibration transmitted by conventional rolling element bearing. Of course, magnetic bearings are power-intensive devices and require complicated feedback and control systems. Precise alignment is also critical.

The improvement in payload mass fraction, or reduction of overall satellite bus mass, is made possible by applying the ESF that combines the functions of energy storage (typically a chemical spacecraft battery) and momentum management (typically an attitude control reaction or momentum wheel) into a single device. The ESF, unlike a chemical battery, can be repeatedly deep discharged and operated in a hot (30–40 °C) spacecraft environment without an adverse effect on its expected life, hence improving mission reliability. To achieve long life, typical chemical batteries in LEO must be maintained at or below a temperature of 20 °C and often complicate or drive the entire spacecraft thermal design. Again, to achieve long life in LEO, chemical batteries are usually shallowly discharged to about 20–40 percent of their rated energy storage capacity. An ESF could be sized for an 85–90 percent discharge every orbit, without sacrificing ESF life. Even if the specific energy of a chemical battery was comparable to an ESF (which is typically higher), the ESF would offer a factor-of-three lighter system, only considering the depth-of-discharge and the excess capacity required to reliably use a chemical battery.

Eliminating separate momentum management wheels and their electronics and harness further reduces system mass. A pair of counter-rotating ESF units is expected to have a significantly smaller mass than the equipment they replace. For a Defense Meteorological Satellite Program (DMSP)-class mission, the mass savings would be on the order of 100 kg. For a geosynchronous communication mission, the mass savings could be three times greater, mainly because of higher power levels. In addition, a chemical battery typically returns about 70 percent of the energy used to charge it. Motor/generators have demonstrated 95-percent round trip charge/discharge efficiency. At the fully integrated spacecraft level, the ESF with magnetic bearings and power processing electronics are expected to maintain an energy return efficiency of about 90 percent. Improved power system efficiency would allow a spacecraft engineer to reduce significantly the size of a satellites solar array, simplify thermal control, and reduce the size of the spacecraft wire harness—all of which save mass and cost.

Finally, since angular momentum and electrical power are interchanged in an ESF, magnetic torque rods or reaction control thrusters and propellant are not required to manage the accumulation of uncompensated momentum on the spacecraft rising from secular torques.

DATA SHEET 19.5. MECHANICALLY PUMPED THERMAL SYSTEMS

Developing Critical Technology Parameter	Mechanically pumped thermal loops enable the efficient collection, transportation, and rejection of waste heat within a spacecraft. Compressing a two-phase working fluid as in a typical heat pump system allows the rejection temperature to be increased so that a smaller radiator can be used. This approach also enables the collection and rejection of large amounts of low-grade heat with a manageable radiator size and the positioning of the thermal radiator in a way that minimizes the thermal signature of a spacecraft. The figure of merit for a pumped thermal system is unit thermal energy rejected per unit electrical energy expended in the pumping system. A target value is a minimum W_{th}/W_{el} figure of merit of four for a temperature lift of 50 °C or greater. Additional important technology parameters include the scale of the system, which should be > 2 kW, and the life performance of the pumping device, which should equal at least 15 years.
Critical Materials	No specific materials have been identified, but the necessary pump technology will probably involve some carefully engineered materials to allow long-term reliability to be achieved.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial spacecraft can use this technology for applications that involve substantial low-grade heat generation, such as communications satellites that include on-board packet processors.
Affordability	The cost of these systems is competitive with current thermal control systems.

BACKGROUND

Thermal control of spacecraft has become a controlling factor in many applications. While the power-generation levels and payload functionality of spacecraft continue to increase, they still must fit within launch vehicle fairing constraints. As a result, a simple passive heat-rejection system becomes insufficient at some point and can become the major barrier to greater functionality.

Capillary-pumped thermal loops remove some of these constraints and make it practical to deploy more radiator surfaces. As the heat is rejected farther from the source and passes through several interfaces, the efficiency of the system drops, however, and radiators can become rather large.

Simple, mechanically pumped loops can be used to provide higher flow rates in single-phase systems and make it easier to collect waste heat from multiple distributed sources. Mechanically pumped loops can be even more effective if they are used in two-phase systems as heat pumps, raising the temperature of the working fluid and rejecting the heat at a significantly higher temperature. This reduces radiator size and facilitates stowing a high heat-rejection capability within existing launch-vehicle dimensional constraints.

Some payload items, such as on-board data processors, produce significant amounts of waste heat but should preferably be compact in size to maintain high performance and cost-effective production. Space pumped loop thermal systems enable the collection of large concentrated heat loads and efficient transportation of the heat to a remote radiator.

SECTION 19.6—PROPULSION FOR SPACE SYSTEMS

Highlights

- Emerging propulsion technology areas include improved chemical, electrical, and solar thermal.
- Solar thermal propulsion (STP) offers an efficient LEO to GEO transfer technology, as well as other space-based maneuvering capabilities.
- Electrical propulsion technologies will be available in several power levels, ranging from low-power systems useful in maneuvering microsatellites/nanosatellites through medium-power to high-power systems useful in orbit raising, space-based maintenance, and other space-based maneuvering applications.
- Developments continue in high energy-density propulsion materials, improved propellant additives, and advanced cryocoolant storage. These technologies will enable longer range and larger payload boosters and more efficient space-based maneuvering.
- New, full-flow rocket engine and fluid-bearing technologies will enable longer lasting and higher performing rocket engines, which will provide a capability for military spaceplane and higher performance space vehicles.

OVERVIEW

Propulsion technologies include three basic categories: chemical (including liquid, solid, and hybrid systems), electrical, and solar thermal. High-energy propellants remain the technology of choice for launch vehicles. Electrical is useful for efficient station keeping and maneuvering and orbit raising. Low-cost solid and low-pressure, high-tolerance liquid propellant, or hybrids, remain useful for first-stage booster propulsion. Solar thermal may be useful in LEO-to-GEO transfer missions. New engine and bearing technologies enable more efficient high-power rocket-propulsion systems.

New technologies supporting STP include large space-based solar concentrators, thrusters, and propellant management systems. The concept is to use concentrated solar power to heat hydrogen and enable a propulsion system I_{SP} in excess of 800 seconds. This propulsion technology will support satellite mobility and LEO-to-GEO transfer missions. Engine technologies that heat refractory material to heat the propellant continuously or that store heat for phased transfer to the propellant are needed.

The development of higher performance propellant ingredients and advanced propellants will yield extended range and expanded payload capacity. Solid and hybrid propulsion technologies include nonhalogenated solid oxidizers, chemical compounds, high-energy binder polymers and monomers, ultrafine materials. Liquid-propellant technologies include high-performance hydrocarbon ingredients for bipropellant systems. High-energy propellant technologies should increase booster I_{SP} by 4–10 percent and propellant density over 2 percent during the next 10–15 years. For spacecraft propulsion, new monopropellant formulations should yield up to 70 percent increase in density impulse over the next decade.

Electric propulsion technologies are divided into low-power, medium-power, and high-power systems. Low-power technologies are most useful in microsatellite/nanosatellite applications for on-orbit propulsion. Medium-power systems are useful in north-south station keeping, orbit topping, and orbit repositioning. High-power systems have potential for orbit raising and orbital transfer vehicles. Advanced Hall thruster materials for longer life, high-saturation flux-density magnetic materials and high Curie temperature permanent magnets, and materials resistant to oxidation for robust hollow cathodes are required.

Cryogenic propulsion fluids, solids, slushes, and slurries must be maintained at temperatures below 100 K, with loss rates of less than 30 percent per year. Advances in this technology are aimed at improving refrigeration and storage efficiencies at cryogenic temperatures and broadening the duration of storage. In addition, the types of fluids need to be broadened to include semisolids and fluorine-based compounds. This requires high fracture toughness in tank materials, more efficient thermal insulation, active thermal insulators, and compatible materials for lines, ducts, tankage, gaskets, and seals.

Full-flow rocket engine technologies that reduce turbine temperatures by increasing the mass flow across each turbine will increase turbine lifetime. Use of oxidizer-rich fluid eliminates requirements for interpropellant seals, which will decrease maintenance requirements. The result should be an order-of-magnitude improvement in operations and comparable reduction in costs. Supporting technologies include modeling of crack initiation in hot, oxygen-rich/steam environments, rocket engine start transient modeling, valve sequencing control, hot gas injection, and high-temperature, oxygen-rich compatible materials.

Hydrostatic bearing technology will enable higher speed rocket turbomachinery. It will eliminate roller bearing load limitations on rotational speeds by providing bearings that use high-pressure fluid films to avoid contact during operations. Technologies need to overcome wear at startup and low speeds. Precision tolerances and sophisticated modeling technologies will be required to transition this technology to space applications.

LIST OF TECHNOLOGY DATA SHEETS
19.6. PROPULSION FOR SPACE SYSTEMS

DATA SHEET 19.6. SOLAR THERMAL PROPULSION (STP)

Developing Critical Technology Parameter

STP uses concentrated solar power to heat hydrogen to high temperatures, enabling the propulsion system I_{SP} to exceed 800 seconds. This high I_{SP} technology is applicable for orbit raising and maneuvering applications and compared with conventional chemical propulsion, enables a doubling of the payload for LEO-to-GEO transfer missions and a threefold increase in satellite mobility. The propulsion system consists of three primary components: large deployable solar concentrators, the thruster, and the propellant management system.

Large deployable solar concentrators, including support structure and pointing elements, collect radiation from the sun and focus it into the thruster. The thruster receives the incident solar power, transfers heat to the propellant, and expands the propellant through a nozzle for propulsion. Two candidate engine technologies are being evaluated. In the direct gain engine, energy from the sun is used to heat a refractory material that heats the propellant continuously. In the thermal storage engine, the sun's energy is stored in the thruster through sensible heat or phase transition energy storage and is transferred to the propellant over a relatively short period of time; The propellant management system stores liquid hydrogen (LH_2) and transfers it to the thruster. Noncryogenic storable propellants can also be used to enable multiyear operations capability without cryocooling. Government and industry development efforts are focusing on concentrator, thruster, and propellant system components and are preparing for flight experiments.

By 2010, projections indicate that improvements in I_{SP} and propulsion system specific mass will enable an approximate doubling of LEO-to-GEO payload. The commercial and military markets for this technology are expected to include orbit raising and spacecraft rendezvous/servicing/orbit maneuvering.

Solar Thermal Propulsion

Parameter	1999	Projected by 2010
Specific Impulse (sec)	800	900
Propulsive Efficiency	0.4	0.4
Thruster + Concentrator Specific Mass (kg/N)	22	10
Tankage Fraction	0.27	0.20

Critical Materials

- **High optical transmission and reflection concentrators.** Currently, the overall collection efficiency, including transmission and reflection losses, is approximately 70 percent. The specific mass of such systems is estimated to be 0.5 kg/m^2. Improvements in overall collection efficiency, with minimal increase in specific mass, would reduce the size and mass of the propulsion system. Concentrator candidates should have the following properties:
  - Collector efficiency (accounting for transmission and reflection losses): > 80 percent
  - Specific mass: < 0.5 k g/m^2
  - RMS slope error: < 2 mrad
  - Size: ~ 5–10 meter in diameter
  - Vacuum-compatible, ultraviolet (UV)-resistant: 3 months–15 years.
- **Formable high-absorptivity/high-emissivity refractory materials.** For direct-gain and energy-storage applications, high-emissivity refractory materials will provide

Critical Materials (continued)	improved energy absorption, and higher hydrogen operating temperatures. Candidate materials should have the following properties: – Absorptivity/emissivity: > 0.7 – Maximum operating temperature range of interest: 2,000–2,700 °C – Gas compatibility: hydrogen at 2,000–2,700 °C. • **Formability.** Material should be machinable or formable so that tubes (a few millimeters in diameter and about 1 m long) and surfaces (~ 100 cm^2 area) can be fabricated. The material should also possess good joining properties, low hydrogen permeability, and good thermal cycling properties (> 100 cycles) from –100°C to maximum temperature. • **High energy-density thermal storage.** Sensible heat and heat of fusion options could be considered; however, heat of fusion storage may offer a near-constant temperature heat addition to the hydrogen propellant. The design of either storage system type must be compatible with high-temperature hydrogen exposure. Candidate materials should have the following properties: – Operating temperature: 1,500–2,700 °C – Energy storage: > 10^6 J/kg – Gas compatibility: hydrogen at 1,500–2,700 °C (nonreacting coatings allowed). • **Thruster integration.** The material must be able to be integrated into the thruster so that concentrator flux efficiently heats the storage material and hydrogen flowing through the thruster is efficiently heated by the thermal storage. The effects of machinability, thermal shock, and density change during phase change should be considered.
Unique Test, Production, Inspection Equipment	Large inflatable optics fabrication techniques and facilities.
Unique Software	Control software for the spacecraft will need to be developed. The commercial market, through its development of orbit transfer software for electric propulsion systems, will provide a significant leveraging opportunity.
Major Commercial Applications	Spacecraft orbit transfer and orbit raising; large space structures.
Affordability	Reduced payload delivery cost is a primary motivation for the development of this technology.

DATA SHEET 19.6. HIGH-ENERGY PROPELLANT INGREDIENTS

Developing Critical Technology Parameter	The development of higher performance energetic ingredients for advanced propellants is an area of high interest because of the significant payoffs in system capabilities (e.g., extended range, faster response, increased lethality and expanded payload/warhead capability) that can be realized with such ingredients. Critical technology parameters for these ingredients can be classified into distinct groups that are delineated by their intended propulsion system application: solid and hybrid propulsion ingredients and liquid propulsion ingredients. The critical parameters for the advanced solid and hybrid propulsion systems ingredients are treated separately from critical parameters for the advanced liquid (monopropellant and bipropellant) systems. • **Solid and hybrid propulsion ingredient critical parameters.** Advanced performance propellant ingredients for solid and hybrid systems are a diverse and important technology focus area. Ingredient types and their critical structural parameters include (1) nonhalogenated solid oxidizers that have an oxygen balance > +20 percent and density > 1.73 g/cm^3; (2) chemical compounds that are near stoichiometric balanced with enthalpy of formation > +66 calorie/g, density > 1.8 g/cm^3, heat of detonation > 1.68 kcal/g, and yield combustion products with an average molecular weight < 27 amu; (3) monomers capable of polymerization to produce high-energy binder polymers that constitute a structural matrix for advanced solid propellants (such compounds are monomers comprised of nitro-, nitrato-, azido-, nitramino-, or other energy-conferring functionalities and may incorporate oxygenated, cyclic functionality such as epoxy or oxetane and polymers resulting from these monomers); (4) compounds that constitute energetic fuels, have low or no oxygen content, and have low molecular weight (< 5,000 amu) (development is focused on strained-ring molecules with positive enthalpy of formation and density greater than 1.2 g/cm^3, high-nitrogen molecules, and metal hydrides); and (5) fuel technology defined by ultrafine (< 1 μm average particle diameter) materials with development focused on metals with average atomic mass generally ≤ 27 amu. • **Liquid propulsion ingredient critical parameters.** High-performance hydrocarbon fuel ingredients for bipropellant systems are a critical technology focus area. This group of ingredients is comprised of strained-ring and/or unsaturated hydrocarbon molecules with molecular property objectives that include a carbon-to-hydrogen ratio close to 1:1; enthalpy of formation > 0 calorie/g; and density > 0.8 g/cm^3. Another critical focus area lies in the development of high-energy, storable liquid oxidizer compounds. The technical effort focused on producing materials that have density > 1.4 g/cm^3 and oxygen balance > +33 percent. The development of suitable energetic ingredients is key to advancing monopropulsion technology. Such ingredients possess density > 1.4 g/cm^3, melting point below 100 °C, and chemical functionalities that include nitro-, nitrato-, azido-, nitramino-, strained-ring and/or unsaturated hydrocarbon and high-nitrogen structures that are incorporated into either nonionic or ionic molecules.
Critical Materials	Precursor materials critical to production of high-energy ingredients include dinitramide-based, trinitromethide-based, tetrazole-based, triazole-based, hydrazines, nitration reagents, other high nitrogen- and/or oxygen-containing materials, and strained-ring compounds (e.g., molecules comprised of cyclopropyl and/or cyclobutyl functionality). Reagents for accomplishing *C*-nitrations, *O*-nitrations and *N*-nitrations are often required for ingredient production. Many of these materials can be used in producing pharmaceuticals, commercial explosives and fuels, and other commercial products.

Unique Test, Production, Inspection Equipment	Specialized equipment and tests necessary for evaluating ingredient characteristics include impact sensitivity tester, friction sensitivity tester, electrostatic discharge sensitivity tester, and liquid adiabatic compressibility (U-tube) tester. Some test, production, and inspection equipment for high-energy materials is common to the explosives industries.
Unique Software	Chemical analysis; reaction analysis codes; chemical structure; estimate of chemical and physical properties of energetic molecules; quality control; performance prediction.
Major Commercial Applications	Satellite launch systems; gun propellants; emergency and auxiliary power units; explosives; vehicular restraint systems.
Affordability	When developed, this technology will increase booster range/payload for same or lower costs.

BACKGROUND

High-energy ingredients are required for increased payload capability, extended range, reduced cost, and the increased ability to meet operational requirements for propulsion systems. Aside from assessments of critical physical and chemical parameters of high-energy ingredient candidates, theoretical analyses of the performance of such ingredients in prospective propellant compositions yield additional and direct evidence of their potential payoff.

New energetic ingredients have the potential to increase fielded solid boost system propellant I_{SP} and density over 5 percent within a 10–15 year development period. Performance increases of this magnitude can equate to hundreds of pounds in extra payload capability (depending on system configuration). Parameters that are key to high-energy ingredients for solid and hybrid booster and/or tactical applications include

- Nonhalogenated solid oxidizers with oxygen balance > +20 percent and density > 1.73 g/cm^3.
- Chemical compounds that are stoichiometrically balanced (or nearly balanced) with enthalpy of formation > +66 calorie/g, density > 1.8 g/cm^3, and heat of detonation > 1.4 kcal/g.
- Monomers capable of polymerization to produce high-energy binder polymers that constitute a structural matrix for advanced solid propellants. Such compounds are monomers comprised of nitro-, nitrato-, azido-, nitramino-, or other energy-conferring functionalities and may incorporate oxygenated, cyclic functionality such as epoxy or oxetane, and polymers resulting from these monomers.
- Compounds that constitute energetic fuels, have low-oxygen or no-oxygen content and are of low molecular weight (< 5,000 amu). Development is focused on strained-ring molecules with positive enthalpy of formation and density > 1.2 gram/cm^3, high-nitrogen molecules, metal hydrides, and compounds composed of fluorine and one or more of other halogens, oxygen, or nitrogen.
- Fuel technology defined by ultrafine (< 1 μm average particle diameter) materials with development focused on metals with average atomic mass generally □ 27 amu.

Energetic ingredients for hydrocarbon-fueled engine boosters are expected to produce fuels with over 4-percent increases in I_{SP} within a 10–15 year development period. Performance increases of this magnitude can also equate to hundreds of pounds in extra payload capability (depending on system configuration). Parameters key to high-energy ingredients for hydrocarbon engine booster applications include

- Strained-ring and/or unsaturated hydrocarbon molecules with molecular property objectives that include a carbon-to-hydrogen ratio close to 1:1, enthalpy of formation > 0 calorie/g; and (c) density > 0.8 g/cm^3.
- High-energy, storable liquid oxidizer compounds, with the technical effort focused on production of materials that have density > 1.4 gram/cm^3 and oxygen balance > +33 percent.

In the case of spacecraft propulsion, high-energy ingredient development over the next 10 years is expected to produce monopropellant formulations that yield a 70-percent increase in density impulse over that of hydrazine. Parameters that are key to high-energy ingredients for monopropellant thruster applications include:

- Density > 1.4 gram/cm^3

- Melting point near or below 100 °C
- Chemical functionalities that include nitro-, nitrato-, azido-, nitramino-, strained-ring and/or unsaturated hydrocarbon and high-nitrogen structures incorporated into either nonionic or ionic molecules.

DATA SHEET 19.6. HIGH-ENERGY PROPELLANTS

Developing Critical Technology Parameter

The development of high-energy propellants is a focus of current materials research because of the possible payoff in system capabilities (extended range, faster response, increased lethality, and expanded payload/warhead capability). Critical technology parameters for these high-energy propellants can be classified into distinct groups delineated by their intended propulsion system application. Consequently, critical parameters for propellants that are key to advanced solid and hybrid propulsion systems are treated separately from critical parameters that are key to advanced liquid (monopropellant and bipropellant) systems.

Such performance payoffs can be compared with the established baselines below.

Propulsion Baselines:

- Solid Booster Baseline Capability (1994): I_{SP} [1,000–14.7 psi] = 248 $lb_f s/lb_m$ (delivered impulse of composite, class 1.3 propellant); Density I_{SPdel} = 16.1 $lb_f s/in^3$
- Hybrid Booster Baseline Capability (1994): I_{SP} [1,000–14.7 psi] = 273 $lb_f s/lb_m$ [delivered impulse of solid fuel grain, liquid oxygen (LOX) injected]
- Hydrocarbon-Fueled Booster Capability (1994): I_{SP} [1,000–14.7 psi] = 261 $lb_f s/lb_m$ (delivered impulse for RP1/LOX system)
- Solid/Hybrid Tactical Motor Capability (1994): $I_{SP\ del}$ [1,000–14.7 psi]
  Minimum Smoke/Reduced Smoke/Smoky = 233/239/247 $lb_f s/lb_m$
  Density $I_{SP\ del}$ = 14.2/15.2/17.9 $lb_f s/in^3$
- Spacecraft Monopropellant and Storable Bipropellant Engine Capability (1994):
  Density I_{SP} [300 psi-vac; 50:1 exp] (theoretical)
  Monopropellant (hydrazine)/Bipropellant (NTO/MMH) 8.4/14.8 $lb_f s/in^3$

Solid and Hybrid Propulsion Ingredient Critical Parameters: Advanced performance propellants for solid and hybrid systems are a diverse and important technology focus area. Preliminary projections for propellant performance parameter improvements are as follows:

- Solid Booster Propellant Capability (2010): I_{SP} [1,000–14.7 psi] = 260 $lb_f s/lb_m$ (delivered impulse of composite, class 1.3 propellant); Density $I_{SP\ del}$ = 16.9 $lb_f s/in^3$
- Hybrid Booster Baseline Capability (2010): I_{SP} [1,000–14.7 psi] = 287 $lb_f s/lb_m$ (delivered impulse of solid fuel grain, LOX injected)
- Solid/Hybrid Tactical Motor Capability (2010): $I_{SP\ del}$ [1,000–14.7 psi]
  Minimum Smoke/Reduced Smoke/Smoky = 265/268/276 $lb_f s/lb_m$
  Density $I_{SP\ del}$ = 16.5/17.4/20.6 $lb_f s/in^3$.

Liquid Propulsion Ingredient Critical Parameters: Preliminary projections for high-performance hydrocarbon fuels for booster engines, storable bipropellants, and high-energy monopropellants are:

- Hydrocarbon-Fueled Booster Capability (2010): I_{SP} [1,000–14.7 psi] = 272 $lb_f s/lb_m$ (delivered impulse for hydrocarbon/LOX system)
- Spacecraft Monopropellant and Storable Bipropellant Engine Capability (2010):
  Monopropellant (Storable)/Bipropellant (Storable) = 14.4/15.1 $lb_f s/in^3$
  Density I_{SP} [300 psi-vac; 50:1 exp] (theoretical).

Critical Materials	**Note:** *See the bottom of this page for definitions of the terms in this column.* Materials critical to production of high-energy propellants can be dinitramide-based (e.g., ADN), trinitromethide-based (e.g., HNF), perchlorate-based (e.g., AP), tetrazole-based (e.g., aminotetrazole), triazole-based (e.g., aminotriazole), azetidine-based (e.g., TNAZ), hydrazine-based (e.g., hydrazine nitrate), hydroxylamine-based (e.g., HAN), other high-nitrogen and/or oxygen-containing materials (e.g., CL-20, HMX, BuNENA, and BTTN), and strained-ring compounds (e.g., molecules comprised of cyclopropyl and/or cyclobutyl functionality). Also critical are high-energy binder monomers that yield polymers that constitute a structural matrix for advanced solid propellants and are comprised of nitro-, nitrato-, azido-, nitramino-, or other energy-conferring functionalities (e.g., NMMO, BAMO, AMMO, glycidyl nitrate, and glycidyl azide). Ballistic modifiers, such as metal resorcylates and salicylates, are often required to produce acceptable propellant regression rate behavior. Also critical are ballistic modifiers capable of generating steady-state burning rates in excess of 1.5 in. per second at 1,000-psi pressure at 294 K (e.g., metals, metal oxides, and solid oxidizers with submicron particle size). Stabilizers for advanced propellants are critical and include N-methyl-p-nitroaniline and Protech.
Unique Test, Production, Inspection Equipment	Specialized equipment and tests necessary for evaluating propellant characteristics include impact sensitivity tester, friction sensitivity tester, electrostatic discharge sensitivity tester, NOL card gap test, combustion window bomb, propellant strand-burner, and liquid adiabatic compressibility (U-tube) tester. Some test, production, and inspection equipment for high-energy materials is common to the explosive industry. Production equipment includes planetary mixers capable of vacuum operation with capacities ranging from 1 pint to over 600 gallons. Other processing equipment includes extruders.
Unique Software	Chemical analysis; reaction analysis codes; chemical structure; estimate of chemical and physical properties of energetic molecules; quality control; performance prediction.
Major Commercial Applications	Satellite launch systems; gun propellants; emergency and auxiliary power units; explosives; vehicular restraint systems.
Affordability	Higher propellant performance will increase booster performance and/or reduce costs of launch for a given size/weight payload.

BACKGROUND

Advanced performance propellants for solid and hybrid systems are a diverse and important technology focus area. In the next 10 years, new and emerging propellant formulations that incorporate high-energy ingredients to achieve increases in I_{SP} and density by 5 percent or greater are expected to be developed. Currently, 70 percent of the launch weight of an upper stage, including the payload, is propellant. This technology is developing new, improved chemical compositions with higher thrust-to-weight ratios. Payload capacities can be increased by hundreds of pounds (depending on the particular propulsion system configuration).

High-energy monopropellant development can be expected to allow for payload increases of > 50 percent over systems currently using hydrazine. Also, satellite life may be extended by 50 percent.

Definition of terms in Critical Materials column above:

Term	Definition
ADN	Ammonium Dinitramide
AMMO	3-Azidomethyl-3-Methyl Oxetane
AP	Ammonium Perchlorate
BAMO	3,3-Bis(3-azidomethyl)oxetane
BTTN	Butanetriol Trinitrate
BuNENA	Butyl-2-Nitratoethyl Nitramine
CL-20	Hexanitrohexaazaisowurtzitane
HAN	Hydroxylammonium Nitrate or Hydroxylamine Nitrate
HMX	Octogen
HNF	Hydrazinium Nitroformate
NMMO	2-Nitratomethyl-3-methyloxetane
TNAZ	Trinitro-azetidine

DATA SHEET 19.6. SOLID-PARTICLE CHEMISTRY OF ENERGETIC PROPULSION MATERIALS

Developing Critical Technology Parameter	The objective of this technology development program is to determine, understand, and control the fundamental reaction dynamics of solid fuel additives (e.g., aluminum and boron metal particulates) with oxidizer intermediates by determining the key parameters of solid particles in energetic materials. This program will develop a database for unimolecular decomposition mechanisms of oxidizers to produce intermediates species; determine the theoretical gas phase structure of the intermediate products; identify the chemical mechanisms and dynamics of oxidizer intermediates with reaction of metal atoms or clusters of metal atoms; develop a first principles/molecular dynamics approach to understand the collision of metal clusters with the theoretically determined gas phase structures; identify and determine the important oxidizer intermediates in high pressure reactions; and determine the intermediate/oxidizer reaction at high pressure
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Satellite launch systems; gun propellants; explosives.
Affordability	The higher energetic materials developed through this technology should reduce launch costs.

BACKGROUND

The solid-particle chemistry program was initiated with early experimental studies of the reaction chemistry of aluminum and boron (particles and foils) in reactive atmospheres at static high pressures during pulsed laser rates as a function of pressure and initial laser energy. In particular, the reaction of aluminum and boron in oxygen and water at pressures up to 2.0 GPa were investigated. Finally, early work on the reaction of aluminum particles in fluorinated compositions at pressures up to 2.0 GPa during pulsed laser heating was completed. From these data, a reactive shrinking core model is being developed to understand boron and aluminum consumption in the combustion, deflagration, and detonation processes.

DATA SHEET 19.6. FLUORINE GAS ENHANCEMENT OF BORON PROPELLANT COMBUSTION

Developing Critical Technology Parameter	This developing technology is investigating fluorine gas parameters in support of enhanced combustion/propulsion. Getting the highest amount of energy per pound of propellant is a key factor in rocket performance. While liquid propellants provide more energy per pound than solid propellants, they are more expensive and difficult to store because they must be cryogenically cooled. Solid propellants are less costly and relatively safe and reliable but are far less energetic. This technology effort explores the use of highly energetic metals (e.g., boron, which has a high heating value per unit mass and volume) as an additive. The drawback is that a thin layer of boron oxide forms on the particles' surface, hindering combustion and delaying ignition. The parameter investigation of highly reactive fluorine is centered on whether fluorine will strip the boron of oxidation and improve the ignition time.
Critical Materials	Fluorine and boron as combustion additives.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This developing technology will have a significant impact on military and commercial boosters if it can be understood and fully used in the combustion of solid rocket motors for space launches and other propulsion applications.
Affordability	This technology has the potential to reduce launch costs significantly.

BACKGROUND

Getting the highest amount of energy per pound of propellant is a key factor in rocket performance. While liquid propellants provide more energy per pound than solid propellants, they are more expensive and difficult to store because they must be cryogenically cooled. Solid propellants are less costly and relatively safe and reliable but are far less energetic.

This technology effort explores the use of highly energetic metals (e.g., boron, which has a high heat capacity value per unit mass and volume) as an additive. This research will use high-speed cameras and spectrometers to analyze how the fluorine enhances the combustion of boron in propellants. This will be done by measuring the spectra of the burning metal in argon and oxygen at high pressure and temperature and monitoring the effects of different concentrations of fluorine gas. An image-converting streak camera will be used to capture time-resolved spectra gathered with a spectrometer to maximize the amount of data gathered.

This developing technology will have a significant impact on boosters if it can be understood and fully used in the combustion of solid rocket motors for space launches and other propulsion applications.

DATA SHEET 19.6. LOW-POWER ELECTRIC PROPULSION

Developing Critical Technology Parameter	Low-power (< 200 W) electric propulsion is the portion of the electric propulsion technology spectrum that has the most enabling technology for microsatellites/ nanosatellites. For these satellites, it provides the only available propulsion. Low-power electric propulsion systems for microsatellites/nanosatellites will provide primary on-orbit propulsion. Other uses include attitude control thrusters for larger, more conventional spacecraft. Thruster types include pulsed plasma thrusters, Hall thrusters, and colloid thrusters. Current development is concentrating on improving efficiency, maximizing propellant use, and reducing thruster mass.
Critical Materials	Many low-power electric propulsion thrusters use capacitors for electrical energy storage. Improved capacitor technology that reduces charge bleed off, internal resistance of large capacitors, and specific charge is vital for the continued development of this field. Pulsed plasma thrusters (PPTs) currently use Teflon® as a propellant. Studies are needed to determine the suitability of other propellants. A propellant with a higher heat of vaporization could result in lower propellant use rates and improved thruster performance. Low-power Hall thrusters are lifetime limited by the erosion rate of the ceramic insulators in the ion acceleration channel—even more so than larger Hall thrusters because of the higher plasma densities. New, low-sputter yield materials need to be developed and tested. Thruster mass can be reduced by the development of higher saturation flux density magnetic materials. High Curie temperature permanent magnets are also needed to simplify the design of the magnetic circuits of Hall thrusters.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Orbit topping; orbit raising; primary propulsion for microsatellites/nanosatellites and attitude control for large spacecraft (i.e., replacement of reaction wheels).
Affordability	This technology will enable simpler, less expensive thrusters for microsatellites/ nanosatellites.

BACKGROUND

Low-power electric propulsion is the driving technology behind the future use of microsatellites/nanosatellites. For these satellites, it is the only available propulsion technology. Low-power electric propulsion will provide small, low-mass, efficient thrusters for attitude control and positioning of small space vehicles. It may also simplify the design and lighten the mass of larger spacecraft, if used for attitude control instead of reaction wheels.

DATA SHEET 19.6. MEDIUM-POWER ELECTRIC PROPULSION

Developing Critical Technology Parameter	Medium power (500 W–5 kW) electric propulsion is the most mature portion of the electric propulsion technology spectrum. Common thruster types include Hall thrusters, arcjets, and ion engines. Of these, arcjets and ion engines are currently commercialized in the United States. Hall thrusters have higher I_{SP} (1,800 s) than arcjets and higher thruster densities than ion engines.
Critical Materials	Hall thruster lifetime is limited by the erosion rate of the ceramic insulators in the ion acceleration channel. New, low-sputter yield materials need to be developed and tested. The thruster mass can be reduced by the development of higher saturation flux density magnetic materials. High Curie temperature permanent magnets are also needed to simplify the design of the magnetic circuits of Hall thrusters. Low-work-function materials with resistance to oxidation are needed to produce more efficient and robust Hall thrusters.
Unique Test, Production, Inspection Equipment	Large vacuum chambers with cryogenic pumping (such as the one at Edwards AFB, California) are required to simulate the space environment during thruster testing.
Unique Software	None identified.
Major Commercial Applications	North-south station-keeping; orbit topping; orbit repositioning; limited orbit raising.
Affordability	This technology should reduce costs of some on-orbit repositioning operations.

BACKGROUND

Electric propulsion offers the advantage of higher I_{SP} (compared with traditional chemical and cold gas thrusters) for missions such as north-south station keeping, orbit topping, and orbit repositioning.

DATA SHEET 19.6. HIGH-POWER ELECTRIC PROPULSION

Developing Critical Technology Parameter	High-power (> 30 kW) electric propulsion is the least studied portion of the electric propulsion technology spectrum. Experimental thruster types include Hall thrusters, arcjets, and ion engines. Although arcjets with powers as high as 100 kW have been developed and tested in the laboratory, their low efficiency and I_{SP} have precluded their commercialization. High-power ion engines are difficult to implement because of grid alignment issues and low-thrust densities. Hall thrusters, which have higher I_{SP} (1,800□s) than arcjets and higher thrust densities than ion engines, are currently considered the best candidates for high-power electric propulsion missions. Missions for high power electric propulsion includes orbit raising and primary propulsion for orbital transfer vehicles (OTVs).
Critical Materials	Hall thruster lifetime is limited by the erosion rate of the ceramic insulators in the ion acceleration channel. New, low-sputter yield materials need to be developed and tested. The thruster mass can be reduced by the development of higher saturation flux density magnetic materials. High Curie temperature permanent magnets are also needed to simplify the design of the magnetic circuits of Hall thrusters. Low-work-function materials with resistance to oxidation are needed to produce more efficient and robust hollow cathodes for Hall thruster beam neutralization.
Unique Test, Production, Inspection Equipment	Large vacuum chambers with high pumping speeds are required to simulate the space environment during thruster testing. M&S efforts will allow larger systems to use currently available facilities.
Unique Software	None identified.
Major Commercial Applications	Orbit topping; orbit raising; primary propulsion for OTVs.
Affordability	High initial cost, particularly for vacuum chambers for testing. By extending technologies developed for medium-power electric propulsion, this technology may yield a cost-effective orbit transfer.

BACKGROUND

Electric propulsion offers the advantage of higher I_{SP} (compared with traditional chemical and cold gas thrusters) for missions such as orbit topping, orbit raising, and primary on-orbit propulsion for OTVs.

DATA SHEET 19.6. STORAGE AND REFRIGERATION—CRYOGENIC PROPELLANT

Developing Critical Technology Parameter	Cryogenic fluids, solids, slushes, and slurries must be maintained at temperatures below 100 K, with loss rates less than 30 percent/year of storage. Cryogenic propellants store a large amount of energy per unit mass and are high-efficiency rocket, missile, air vehicle fuels, and lasers. LOX and LH_2 are the current state-of-the-art fluids. Research is continuing on liquid fluorine, nitrogen/fluorine compounds, oxygen/fluorine compounds, slush hydrogen (also referred to as increased density propellants), slush oxygen, and doped hydrogen and oxygen slurries. Cryogenic storage and refrigeration systems include fluid-compatible and impermeable materials (tankage and seals), active and passive insulation systems, high-efficiency pumps and condensers, heat exchangers, near-zero thermal shrinkage materials, and environmentally benign refrigerants. Advances in this technology are aimed at improving the refrigeration and storage efficiency at cryogenic temperatures, lengthening the duration of storage, broadening the types of fluids stored (to include semisolids), and storing fluorine-based compounds.
Critical Materials	Oxygen-compatible tankage materials; high-fracture toughness cryogenic tank materials; efficient thermal insulation; active thermal insulators; compatible line, duct, tankage, gasket, and seal materials.
Unique Test, Production, Inspection Equipment	Cryogenic fluids for testing and chemicals passivation; production—friction stir welding; low- or zero-gravity test facilities; vacuum jacketed equipment.
Unique Software	Adaptable for current simple control logic.
Major Commercial Applications	Except for the use of LOX, which is a common industrial chemical used in welding and the medical industry, commercial applications for these technologies are specialized niche markets (e.g., launch vehicles, satellite propulsion, upper-stage propulsion, liquefied gas industry, and specialty chemical processes).
Affordability	These technologies, though expensive, tend to increase heavy lift capability, thus increasing the effectiveness of an on-orbital asset. They avoid the need for on-orbit assembly.

BACKGROUND

This technology contributes to specialized electromagnetic devices and superconductors. In the 1960s, DoD and NASA were investigating the use of fluorine and nitrogen/fluorine compounds for rocket propulsion. In the mid-1990s, the commercial industry and DoD were conducting research into reducing cryogenic fluid loss rates and increasing refrigeration efficiency.

DATA SHEET 19.6. FULL-FLOW STAGED COMBUSTION ROCKET ENGINE CYCLE

<table>
<tr><td>Developing Critical Technology Parameter</td><td>The full-flow staged combustion engine cycle reduces turbine temperatures by increasing the mass flow across each of the turbines. A fuel-rich fluid drives the fuel turbopump turbine, as in the Space Shuttle Manned Explorer (SSME). However, an oxidizer-rich fluid drives the oxygen turbopump and eliminates the requirement for an interpropellant seal. The resulting reduction in temperature will increase the lifetime and decrease the maintenance requirements of the turbines, resulting in an order-of-magnitude improvement in operations and support (O&S) costs. The elimination of the interpropellant seal eliminates a critical failure mode.
The critical requirements for this advancement are materials that can withstand the hot, oxygen-rich environment (oxygen partial pressures in excess of 5,000 psia) without igniting and combusting. Resulting lower turbine temperatures also allow in the hydrogen turbopump turbine the use of materials that are inherently resistant to hydrogen embrittlement. The focus of this engine cycle is to achieve greatly improved life and operability with the same performance as the SSME.
<table>
<tr><th>Parameter</th><th>1999 (SSME)</th><th>2003</th></tr>
<tr><td>Turbine temperature</td><td>1878 R fuel
1469 R ox</td><td>1430 R fuel
1274 R ox</td></tr>
<tr><td>Cycle life</td><td>10</td><td>200</td></tr>
<tr><td>Mean time between overhaul (MTBOH) (cycle or flight)</td><td>1</td><td>100</td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Oxygen-rich, compatible materials at temperatures indicated above for 2003. Higher use temperatures are sought for additional performance improvements.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Requires data on material performance in a hot, oxygen-rich steam environment, which, in turn, requires special test apparatus; measurement of stress-corrosion cracking.</td></tr>
<tr><td>Unique Software</td><td>Modeling of crack initiation and growth in hot, oxygen-rich/steam environment required; rocket engine start transient modeling.</td></tr>
<tr><td>Major Commercial Applications</td><td>Commercial launch services, including technology applications for reusable and expendable vehicles.</td></tr>
<tr><td>Affordability</td><td>This technology will reduce required maintenance and support on reusable launch vehicle engine systems. It will also provide low-cost and rapid access to space.</td></tr>
</table>

BACKGROUND

The full-flow staged combustion engine cycle is the next significant advancement of rocket propulsion. The demonstration of key technologies that overcome oxygen-rich environment issues and gas-gas injection will benefit future propulsion systems.

DATA SHEET 19.6. HYDROSTATIC BEARINGS FOR ROCKET ENGINE TURBOMACHINERY

Developing Critical Technology Parameter	Up to the present time, rocket engines have exclusively used rolling element bearings, which are subject to extreme loads and wear in rocket engine turbomachinery. In cryogenic propellants, no suitable lubricant is available, and, instead, the propellant acts as a coolant. Rolling element bearings also suffer from rotational speed limits, which reduce the rotating speed of rocket engine turbomachinery. Hydrostatic bearings are a class of fluid film bearings that have no contact during operation because the surfaces are separated by a very high-pressure film of fluid. Because there are no contacting surfaces, there are no bearing speed limits, and this allows substantial increases in rocket turbomachinery speed, which leads to meaningful weight reductions. This tribological study of reduced friction and longevity will be required to determine suitable materials. In addition, the fluid film has significant damping, which results in superior rotordynamic performance. Because the propellants are the source of the high-pressure fluid film in hydrostatic bearings for rocket turbomachinery at startup and shutdown when propellant pressures are lower, some wear may take place at low-load conditions. For this reason, material selection for bearings and journals is very important.
Critical Materials	Tribological pairs for rotor/bearings, which show low friction and wear at startup and shutdown conditions. This is usually a hard-on-soft material combination.
Unique Test, Production, Inspection Equipment	Precise tolerances are required. The ability to predict radial and axial stackups and tolerances accurately is critical.
Unique Software	Special codes have been developed to predict stiffness, damping, and other features of hydrostatic bearings. The compressible nature of LH_2 in rocket engine applications makes this a niche application.
Major Commercial Applications	Fluid-film bearings are routinely used in commercial industry. They have not been applied to rocket engine turbomachinery because of the complexity involved in modeling these bearings in high-speed rotating environments with compressible fluids (LH_2).
Affordability	Hydrostatic bearings impact affordability because they result in an order-of-magnitude reduction in parts and allow easier assembly. In addition, the more benign rotordynamic environment and longer bearing life will drastically reduce required rocket turbomachinery maintenance and associated costs.

BACKGROUND

Hydrostatic bearings are being developed for rocket engine turbomachinery applications because they support requirements for longer rocket engine life and a significant reduction in operation and maintenance (O&M) costs. Increased performance is a side benefit that results from higher operating speeds and lower turbomachinery weight.

DATA SHEET 19.6. ROCKET TURBOMACHINERY DESIGN AND MODELING

Developing Critical Technology Parameter	This effort will improve rocket engine turbomachinery design and modeling. This includes axial and radial loads prediction, rotordynamic performance prediction, and impeller, volute, diffuser, nozzle, and turbine component design and performance prediction. Great strides have been made in such modeling for gas turbine engines; however, because of the far smaller market for rocket engines, the technology transfer from the gas turbine industry to the rocket turbomachinery industry has been slow. Recently, for example, improvements have been made in applying high-stage loading centrifugal compressor technologies to LH_2 pump impellers. The recent availability of low-cost, high-performance desktop computers and software applications has resulted in substantial gains in this area at several U.S. high- technology companies.
Critical Materials	Software codes and laboratory test data for validating these predictive tools.
Unique Test, Production, Inspection Equipment	Laboratories for evaluating and measuring pump and turbine performance, including pressures, temperatures, and velocities; laser imaging of simulant flows; rocket engine turbomachinery test stands for performance measurements.
Unique Software	Fluid flow models for rotating machinery passages; bearing performance software and rotordynamic software; axial and radial load models; and so forth.
Major Commercial Applications	Commercial pumping industry; power-generation industry; water industry.
Affordability	This technology will Improve performance (efficiency) and reduce maintenance for pumps. Commercial pump users will realize massive energy savings and smaller but significant savings on pump maintenance costs.

BACKGROUND

Rocket engine turbomachinery design and performance tools do not match the standards of the tools for conventional gas turbine engines. The ability to model and predict axial and radial loads, rotordynamic performance, and improved impeller, volute, diffuser, nozzle, and turbine component performance will yield more efficient designs for space applications. Because of the large and important domestic and international market in gas turbine engines, great strides in this area have been made in the past two decades. However, even though rocket engines do not enjoy a large market, these engines will benefit substantially from the technology transfer from the gas turbine industry. This technology area is already realizing some progress.

SECTION 19.7—RESERVED

SECTION 19.8—SENSORS FOR SPACE SYSTEMS

Highlights

- Space sensor technologies improve the accuracy and timeliness of surveillance systems for improved battlefield awareness and space control.
- IR sensors are the key elements in sensor systems, such as the Defense Support Program (DSP) and the Space-Based Infrared System (SBIRS), which support National Missile Defense (NMD) and Theater Missile Defense (TMD) missions. Electronic intelligence (ELINT) sensors detect ships at sea, mobile and fixed radars, and so forth.
- Synthetic aperture radar (SAR) is particularly well suited to space applications, and researchers are investigating many new high-resolution improvements in this technology area.
- Advanced sensor technologies will exploit advances in multispectral target phenomenology, signal processing, large constellation satellite architectures, low-power, high-performance computing, and low-cost microelectronics to develop advanced surveillance systems.
- Quantum well IR photodetectors (QWIPs) are particularly useful for space surveillance of cold objects. Their multispectral capability can be used in an NB mode with high-resolution multispectral and hyperspectral response for greater discrimination between targets or in a mode that produces a very broadband response.
- Hyperspectral imaging has two promising defense applications: characterizing the battlespace environment and prosecuting tactical targets.
- Advanced space-based radar technologies will lead to a new generation of space-based intelligence, surveillance, and reconnaissance (ISR) radar systems. They rely on advanced radar algorithms, high-power aperture and sparse aperture concepts, MMICs, RF photonics technology, and low-power, high-performance computing.
- Technologies for fabricating and optimizing thin silicon windows materials for space sensor applications are useful in detecting nuclear detonation in space and monitoring space weather.

OVERVIEW

Technologies supporting space-based electrooptic and radar sensors are critical to U.S. national security. These sensors allow the examination of points on or near the earth. In cases where scattered sunlight or thermal radiation is not adequate to form images of sufficient detail and clarity, laser illumination can be used as an augmenting source of light. They are a major part of tactical and strategic data collection. See Section 11, *Laser and Optics Technology*, Section 16, *Positioning, Navigation, and Time Technology*, and Section 17, *Sensors Technology*, for nonspace applications.

LIST OF TECHNOLOGY DATA SHEETS
19.8. SENSORS FOR SPACE SYSTEMS

DATA SHEET 19.8. QUANTUM WELL IR PHOTODETECTORS (QWIPs)

Developing Critical Technology Parameter	The natural line width for QWIPs is quite narrow (of the order of a micrometer or less), so growing several devices in tandem so that each operates at a different wavelength leads to a device that has multiple narrow-line responses—from the short-wave IR to the very-long-wave IR. This addresses several technical needs, such as tunable hyperspectral sensors, hyperspectral signal processing, high-speed uniform focal-plane arrays (FPAs), improved sensitivity/higher yield optical sensors, and background/target discrimination. This effort, by using the results from single-color and multicolor QWIPs technology development, will produce QWIPs that interact with dozens of IR wavelengths, each response being very NB and resulting in a high-resolution hyperspectral detector. This developing technology will concentrate on the growth of test devices in the mature n-type GaAs technology to ensure high reproducibility and high uniformity. This hyperspectral application must investigate voltage tunability. Current QWIP designs rely on electrical connections to the various layers of the pixel that detects the various wavelengths, resulting in a loss of detecting surface area. To reach a hyperspectral range in which dozens of wavelength responses are possible, the loss of surface area will be great. The full surface area of each pixel will then be available for each wavelength the device was designed to detect. Using n-type GaAs technology requires normally incident light to be turned by a grating to ensure absorption within the quantum wells. Therefore, a hyperspectral grating must be developed. Several possibilities will be investigated: multiperiod ring gratings, multiperiod random gratings, and a novel nonlinear self-tuning grating concept. To keep other options open, alternate materials (e.g., p-type doping and strained-layer superlattices for QWIP design) will be considered. These alternate materials may result in slightly lower uniformity or reproducibility but may provide enhanced wavelength ranges, increased coupling efficiencies, lower dark currents, or higher operating temperatures.
Critical Materials	Alternate materials including p-type doping and strained-layer superlattices for QWIP design.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology will spur the development many new commercial applications. The prime candidates include temperature profiling of buildings to determine heat-loss and vegetation monitoring (e.g., that of fungus and molds on plants, which produce different reflectances and temperatures).
Affordability	When developed, this technology will make hyperspectral imaging from space and space surveillance of cold objects more affordable.

DATA SHEET 19.8. MID-IR LASER SENSOR SYSTEMS

Developing Critical Technology Parameter	This developing technology includes two CO_2 laser sensor systems (the FL and the MFL) that differ in their measurement energy, pulse repetition rates, compactness, and applications. The FL is further along in its development and is bigger in mass (180□), volume (1,400□), measurement energy (40□), and transmitter power (10□) than the MFL. Research goals for both devices are targeted at reducing mass and volume, demonstrating functionality for multiple applications, and developing high-speed signal processors for their different waveforms. The wavelength agile operation is accomplished with a galvanometer-driven grating, and this capability is fully automated but under operator control. The FL waveform repertoire provides tracking, imaging, and chemical-agent detection capabilities. The CO_2 chemical-weapon detection goal is to provide tens of minutes of warning for a concentration of nerve agent at a few parts per million at significant ranges. Key technologies being developed for this program include lightweight materials and new materials development programs. New, highly efficient acoustic/optic (A/O) modulators need to be developed. Agent-detection algorithms also need to be developed and demonstrated. Then, space qualification design and testing will be carried out on all the components.
Critical Materials	New lightweight materials for laser applications in space; small, compact RF power supplies; environmentally stable materials for space applications of laser sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Space telecommunications will use this technology when it has been demonstrated and perfected.
Affordability	When this technology is developed, it should yield economical interceptor and precision surveillance sensors.

BACKGROUND

Research goals for the field LADAR (FL) and the multiple-folded laser (MFL) are targeted at reducing mass and volume, demonstrating functionality for multiple applications, and developing high-speed signal processors for their different waveforms. The FL is further along in its development and is bigger in mass (180□), volume (1,400□), measurement energy (40□), and transmitter power (10□) than the MFL.

The MFL developing technology program will demonstrate a 6-m cavity length CO_2 laser transmitter with an 8-L volume, a 15-kg mass, and a high-quality output beam to produce 250 W of continuous wave (CW) power.

The FL has a 6-m resonator and a discharge volume of 7.2 L. It produces 37 J and has a pulse repetition frequency of 30 Hz. The FL's average power is in excess of 1 kW. The wavelength agile operation is accomplished with a galvanometer-driven grating. This capability is fully automated but under operator control.

DATA SHEET 19.8. LASER RADAR (LADAR) SATELLITE IMAGING TECHNOLOGY

Developing Critical Technology Parameter	This technology development effort concerns identifying and imaging LEO satellites. A LADAR capable of providing range and cross-range measurements of LEO satellites and space debris has to be developed and demonstrated. The LADAR system must also provide active imaging of satellites. The laser must be frequency agile, and its heterodyne detection system must be able to demonstrate remote sensing capabilities. An additional technical development that includes data collection for use in imaging model and algorithms is needed. An in-house LADAR capability needs to be established to acquire data for the development of algorithms. It needs to provide information about target health and status (e.g., whether a satellite is spinning) and to generate a Doppler image of the target. This technology program also has the potential of being able to detect and characterize smaller space debris than that which can currently be detected and characterized.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Developing algorithms for data processing; developing imaging models for interpreting and evaluating system performance.
Major Commercial Applications	None identified.
Affordability	When this technology is developed, it should aid in detecting satellite problems and space debris, which may enable corrective actions to restore satellite health or preventive actions to avoid collisions and produce overall space program savings.

BACKGROUND

The development of imaging models for interpreting and evaluating system performance and of algorithms for data processing is a key aspect of this program. Additional efforts will be examined for use in extremely-high-accuracy satellite ephemeris data and possible use for space debris measurements.

The High Performance CO_2 Laser Radar (Hi-CLASS)[4] will provide much more accurate element data sets for targets of interest. It will also provide information about the target health and status (e.g., whether a satellite is spinning) and generate a Doppler image of the target. In addition, this technology program also has the potential of being able to detect and characterize smaller space debris than that which can currently be detected and characterized.

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[4] The Hi-CLASS effort is a Congressionally mandated program to build a CO_2 laser at the Air Force Maui Space Surveillance Site (MSSS) to work in conjunction with the Advanced Electro-Optical System (AEOS) passive sensor. Hi-CLASS will use the laser to image satellites. AEOS is a Congressionally-mandated program for the construction and integration of a primary telescope at MSSS on Mt. Haleakala.

DATA SHEET 19.8. ADVANCED SURVEILLANCE SYSTEM TECHNOLOGY

Developing Critical Technology Parameter	This technology program will develop a new generation of space reconnaissance systems based on spectrally adaptive imaging sensors. To develop advanced surveillance systems, it will exploit recent advances in multispectral target phenomenology; signal processing, large constellation satellite architectures, low-power, high-performance computing, and low-cost microelectronics. This research will develop and demonstrate a targeting and imaging system at mmW (W-band) frequencies.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Advanced radar algorithms.
Major Commercial Applications	Once this technology is fully developed, it will support a variety of commercial communication applications. In addition, area mapping and other ground-monitoring applications could be supported.
Affordability	No cost savings have been identified. However, as this technology is fielded, the greater accuracy and improved timeliness in surveillance should lead to effective and more efficient use of other resources.

DATA SHEET 19.8. MILLIMETER WAVE TARGETING AND IMAGING SYSTEM (MMWTIS)

Developing Critical Technology Parameter	MMWTIS is a space sensor effort that will enhance battlefield awareness by improving the accuracy and timeliness of surveillance systems. This developing technology exploits recent advances in multispectral target phenomenology, signal processing, low-power, high-performance computing, and low-cost microelectronics to develop advanced surveillance sensor systems.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Area mapping and crop monitoring are two possibilities.
Affordability	A revolutionary reduction in satellite per-unit on-orbit costs ($75–$100M) is needed if concept implementation is to be affordable.

DATA SHEET 19.8. HYPERSPECTRAL IMAGING

Developing Critical Technology Parameter	This technology development concerns the design and development of high-resolution imaging spectrometers. It incorporates high-speed FPAs and grating instruments to provide terrestrial images where wavelength discrimination is required.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology development is expected to have major impact on the commercial sector. Recognized commercial applications range from urban planning to crop yields, from disease vectors to hydrology, from mining to recreation, from fishing to disaster relief. Without doubt, applications not even foreseen will develop as the commercial sector recognizes new opportunities.
Affordability	This is an area where clear commercial benefits are evident. To manage costs, we need to leverage commercial developments, where available, for military capability.

BACKGROUND

The promise of major economic benefit is also encouraging. In recent years, a strong market has developed for data collected by space-based systems such as LANDSAT, SPOT, and RADARSAT. These systems build on markets that use aircraft-collected data. A good market already exits for aircraft-collected hyperspectral data, and a strong market will probably also develop for hyperspectral data collected by space-based systems.

DATA SHEET 19.8. HYPERSPECTRAL PROCESSING

Developing Critical Technology Parameter	This technology concerns processing the huge amount of data collected by hyperspectral sensors and involves advanced processors and software.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Note identified.
Unique Software	The vast amount of data from hyperspectral sensors precludes human processing and has the potential to clog current communication links. Therefore, new algorithms and software will be required. First, new software is required to collect and store the data efficiently on the spacecraft. New data-compression software is also required to reduce the size of the downlink data stream. A high degree of system autonomy is desirable so software that be adapted as needed.
Major Commercial Applications	This technology development is expected to have major impact on the commercial sector. Recognized commercial applications range from urban planning to crop yields, from disease vectors to hydrology, from mining to recreation, from fishing to disaster relief. Without doubt, applications not even foreseen will develop as the commercial sector recognizes new opportunities.
Affordability	This is an area where clear commercial benefits are evident. To manage costs, we need to leverage commercial developments, where available, for military capability.

BACKGROUND

Hyperspectral imaging sensors have the capability to overwhelm existing data channels and provide vast amounts of data. Additional processing at the sensor(s) will be required to reduce the impact on downlinks and other data transmission channels and to ease the burden on analysts.

DATA SHEET 19.8. SPACE-BASED RADAR (SBR)

Developing Critical Technology Parameter	This technology program will develop a new generation of space-based ISR radar systems. It will demonstrate the technical feasibility and cost affordability of a space-based system that offers high-range resolution ground moving-target indication (HRR GMTI), airborne moving-target indication (AMTI), SAR imaging and high-resolution digital-terrain-mapping data-collection capabilities that enable the direct downlink of collected data to theater ground stations. The aperture sizes depend on the to-be-developed active/passive system concepts (SAR/illuminator/passive radiometer) operating from tactical or medium-altitude endurance unmanned aerial vehicle (MAE UAV) operational altitudes. This program will pursue advanced radar algorithms, high-power aperture concepts, sparse aperture concepts, intelligent incorporation of MMICs RF photonics technology, and low-power, high-performance computing.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Advanced radar algorithms will need to be developed.
Major Commercial Applications	This technology once it is fully developed, will generate a variety of commercial remote sensing applications.
Affordability	No cost savings have been identified at this point. However, as this technology is fielded, the greater accuracy and improved timeliness in surveillance should lead to effective and more efficient use of other resources.

BACKGROUND

To develop advanced surveillance systems, this technology effort will exploit recent advances in signal processing, large constellation satellite architectures, low-power, high-performance computing, and low-cost microelectronics. This technology development program carries crossover technologies and leverages major investments already made in photonics, antennas and space-time adaptive array processing with the latest advances in digital receivers.

DATA SHEET 19.8. FABRICATION MATERIALS FOR THIN SILICON WINDOWS

Developing Critical Technology Parameter	This technology development effort will determine the parameters that optimize the fabrication of thin-film material. Research will explore the use of carbon as an etch-stop material for window fabrication, since it has a much higher etch selectivity. This new material is referred to as SiGeC, or silicon-germanium carbon. SiGeC appears to be a superior thin window material for space sensor applications (e.g., X-ray interferometers and detectors, windows for electron sources, windows for X-ray microscopes, and thin transmissive windows for other space radiation of particular interest). Development work will be done on the optimum carbon and germanium concentration for specific applications. Also, the thinnest window that can be fabricated for a given area established. Finally, a theory that explains the etch-stop behavior of this new material needs to be developed.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial space sensor satellites will benefit from this development.
Affordability	When developed, this technology should lead to improved detection of space weather and X-ray signals in space, yielding greater longevity and survivability of space assets.

BACKGROUND

Space weather issues are a serious concern for users of space assets. Developing long-lived, reliable, and economical vehicles requires a solid knowledge of the space environment. For example, the specification and testing of surface materials (e.g., thermal blankets and lens coatings) require environmental specifications gleaned from measurements of low-energy particles in space.

This development effort will explore the use of carbon as an etch-stop material for the fabrication of thin silicon windows. It has produced one of the largest thin silicon windows ever made—0.4 μm thick with an outside frame dimension of 24 mm × 24 mm. The preferred method to fabricate such windows is to diffuse approximately 1-percent boron (atoms) into the surface of a silicon wafer and then chemically etch away the undiffused silicon from the other surface. This is the so called p-stop etch method, which takes advantage of the reduced etch rate of silicon when it is doped with a heavy concentration of boron. Germanium is usually added to compensate for the tensile stress caused by the boron. This material is referred to as SiGeB, or silicon-germanium boron.

So far, research has explored the use of carbon as an etch-stop material for window fabrication since it has a much higher etch selectivity. This new material is referred to as SiGeC, or silicon-germanium carbon. The silicon wafers used in this research were (100) orientation, with a thickness of 530 μm and a diameter of 100 mm. A carbon/germanium-doped silicon film was grown by epitaxy on the surface of these wafers. The thickness of the epitaxial layer in our wafers (which eventually determines the window thickness) ranged from 0.1 μm to 1 μm. Various amounts of Germanium (18–40 percent) were added to carbon-doped layers to compensate for the stress caused by the carbon. The wafers were coated with a 1,000-Å-thick film of silicon nitride by low-pressure chemical vapor deposition (LPCVD).

DATA SHEET 19.8. OPTIMIZATION OF THIN SILICON WINDOWS

Developing Critical Technology Parameter	Entrance window thickness (often referred to as the "dead layer") is a critical factor in some space applications of silicon detectors. These applications include measuring radiation belt and interplanetary ions, especially heavy ions (ion energy < ~ 100 keV); measuring energetic neutral atoms (ENAs) (atom energy < ~ 100 keV); measuring soft X-rays from natural and man-made sources.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified. (Equipment currently exists for characterizing entrance window thickness.)
Unique Software	None identified.
Major Commercial Applications	A current "commercial" driver is the space science missions funded by NASA and the European Space Agency (ESA). While the numbers of devices required are relatively small, these needs drive the technology. Nuclear science research in the heavy-ion area also has a keen need for thin window devices. Thin windows are under consideration for use in electron microscopes.
Affordability	When developed, this technology should lead to improved detection of space weather and X-ray signals in space, yielding greater longevity and survivability of space assets.

RATIONALE

Space weather issues are a serious concern for users of space assets. Developing long-lived, reliable, and economical vehicles requires a solid knowledge of the space environment. For example, the specification and testing of surface materials (e.g., thermal blankets and lens coatings) require environmental specifications gleaned from measurements of low-energy particles in space.

DATA SHEET 19.8. SURVEILLANCE OF SPACE FROM SPACE

Developing Critical Technology Parameter	Metric accuracy greater than 4 arcsec with a goal of 2 arcsec; detection sensitivity greater than 15th visual magnitude with a goal of 20th visual magnitude; field of view greater than 5 × 5 deg; ability to track deep space and near-earth objects; maximum of 30 sec per look to slew and search.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	A large amount of unique software will probably be required, depending on the system design. Likely areas include algorithms to achieve the required pointing accuracy, integration of pixel data, and on-board processing to minimize downlinked data.
Major Commercial Applications	None identified.
Affordability	When available, this technology should provide reduced ground operating costs.

SECTION 19.9—SURVIVABILITY IN SPACE

Highlights

- Space systems must be designed better, specifically to provide a higher success rate for the payload to withstand forces of launch and to be highly reliable on orbit.
- The following components are present in different concentrations in various orbits: energetic, charged particles; UV radiation; atomic oxygen; space debris and micrometeorite particles; and temperature fluctuations. New technologies are being developed to provide improved protection from these elements and from radiation.
- Spacecraft survivability requires materials that can withstand the degradation and erosion caused by simultaneous impact of these components, without producing excessive out-gassing or the stressing conditions related to large temperature gradients. Several developing technologies are addressing this area of research.

OVERVIEW

The space environment is uniquely harsh. Space systems must be designed better, specifically to provide a higher success rate for the payload to withstand forces of launch and to be highly reliable on orbit, in the face of the extremes of temperature, particle impacts, ionic reactions, and radiation.

Many spacecraft anomalies are attributed to the impact of the ionizing-particle environment on space systems. Space systems must be designed to survive the simultaneous impact of the various components of the space environment. Materials for space structures must be chosen to withstand the rigors of the space environment, without producing excessive out-gassing or the stressing conditions related to large temperature gradients. Developing technologies, such as advanced energetic-particle detectors for use in space, can assist in characterizing the space environment and the risks for future generations of space systems.

A significant number of spacecraft operational anomalies are attributed to the effects of the ionizing-particle environment on microelectronic systems. An improved understanding of the high-energy radiation environment in near-earth space and the upper atmosphere and of the effects of this environment is required to reduce future concerns. To assist in the design of future systems, improved models are required for this environment and for the expected changes in the environment caused by solar and solar-terrestrial activity.

Developing technologies include advanced energetic-particle detectors for use in the upper atmosphere and in space and systems for measuring the intensity, energy, and composition of the ionizing-particle radiation and for mapping ionizing-particle radiation in the atmosphere and near-earth space. These technologies will be based on the analyses of large databases of the ionizing-radiation measurements and the sources and transport mechanisms of this radiation, with continued improvement in theoretical models of ionizing-particle radiation and its propagation in space. This will enable researchers to evaluate the effects of this radiation on spacecraft, electronic systems, sensors, and other components.

Protecting spacecraft against the natural space environment is critical for the survivability of assets. The space environment's attack on spacecraft materials is much more extensive and complex than originally thought. While the space environments differ depending on the orbital altitude, the following components are present in different concentrations in various orbits: energetic, charged particles; UV radiation; atomic oxygen; space debris and micrometeorite particles; and temperature fluctuations.

The survivability of spacecraft over the extended periods of time during which their critical components must operate within specific parameters requires the development of materials that can withstand the degradation and erosion caused by the space environment without producing excessive out-gassing or the stressing conditions related to large temperature gradients. This can only be accomplished by a fundamental understanding of the complex reaction processes that take place during the exposure of materials to the space environment.

LIST OF TECHNOLOGY DATA SHEETS
19.9. SURVIVABILITY IN SPACE

DATA SHEET 19.9. SPACE ENVIRONMENTAL IONIZING-PARTICLE DETECTORS

Developing Critical Technology Parameter	The technical objective of this developing technology program is to understand and parameterize the ionizing-particle environment for DoD and civilian space systems for structural components, electronics, and personnel. The specific technology parameter objectives of this effort include (1) the development of advanced energetic-particle detectors for use in the upper atmosphere and in space; (2) the design, fabrication, and development of systems for measuring the intensity, energy, and composition of the ionizing-particle radiation and for mapping ionizing-particle radiation in the atmosphere and near-earth space; (3) the analysis of large databases derived from experiments to improve our knowledge of the ionizing-radiation environment and the sources and transport mechanisms of this radiation; (4) the improvement in theoretical models of ionizing-particle radiation and its propagation in space; (5) the development of engineering assessment tools to evaluate the effects of this environment on spacecraft; aircraft electronic systems, and sensors; and spacecraft and aircraft crews; (6) the investigation of the sources of energetic particles; and (7) the collaboration with other government, academic, and industrial research establishments conducting research in the high-energy space environment to maximize scientific return to the Services and to assist in training personnel for future programs.
Critical Materials	Semiconductor materials for these detectors, microelectronic circuits, and passive ionization sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms that can be used by government, industry, and university personnel to design space systems for operation in the radiation environment; simulations and modeling and data fusion.
Major Commercial Applications	This technology could benefit future commercial payloads, but the impact is not well known at this time.
Affordability	A better understanding of the ionizing-particle environment should enable more efficient spacecraft design and improve performance on orbit, which should decrease overall life-cycle costs of new generations of spacecraft.

BACKGROUND

A significant number of spacecraft operational anomalies are attributed to the effects of the ionizing-particle environment on microelectronic systems. An improved understanding of the high-energy radiation environment in near-earth space and the upper atmosphere and of the effects of this environment is required to reduce future concerns. To assist in the design of future systems, improved models are required for this environment and for the expected changes in the environment caused by solar and solar-terrestrial activity.

Understanding the ionizing particle environment in space is needed to increase longevity of our space assets. Our knowledge base will be increased through the (1) analysis of data from previous experiments, (2) correlative investigations using data from government laboratories, universities, and foreign institutions, and (3) theoretical modeling of the sources, propagation, and confinement of energetic-particle radiation. The program plan is to continue work on the model of the trapped anomalous cosmic ray belt and extend this model to higher altitudes, where the electron stripping probability becomes low and partial stripping and multistage stripping may play an important role, and to higher energies, where the energy dependence of the stripping cross sections becomes important.

DATA SHEET 19.9. SPACECRAFT SURVIVABILITY AGAINST THE NATURAL SPACE ENVIRONMENT

Developing Critical Technology Parameter	This technical development program will address the long-term environmental impact of the simultaneous interaction of combinations of space environmental components and particular materials of interest. Presently, the synergistic interaction of space environmental components (ionic interactions, radiation, out-gassing, and particulate bombardment) and particular materials specifically chosen for subsystems (e.g., thermal radiating services, optical coatings, structural surfaces, and so forth) is not well understood. Consequently, programs that explore this interaction must be carried out over a reasonable period of time to ensure the selection and use of materials that will enable the successful completion of designated missions. To make space assets economically viable for military and commercial use, they must have useful lifetimes of 10 years or more and perform their missions within designated critical parameters. The contamination of optical surfaces by out-gassing of volatile materials or by debris-generated clouds is an example of critical subsystem deterioration that can be expected over extended periods of time.
Critical Materials	Organic polymer materials; optical coatings; high-emissivity, low-absorption materials; solar panel, cover-glass materials, and so forth.
Unique Test, Production, Inspection Equipment	To understand the combined interaction of the space environment with specific materials, a space environmental simulation chamber be available. This chamber must be able to expose materials *simultaneously* to the space environmental components.
Unique Software	None identified.
Major Commercial Applications	This technology will benefit commercial space imaging, particularly when using optical space telescopes, which extremely low contamination rates because of out-gassing and hypervelocity debris impact.
Affordability	The survival of the spacecraft in the natural space environment is an important affordability issue because the degradation of critical capabilities below mission criteria on a satellite in orbit after only a few years requires its replacement with another satellite.

BACKGROUND

Protecting spacecraft against the natural space environment is critical for the survivability of U.S. assets. The results of 5-1/2 years of experiments at the Duration Environmental Facility in Low-Earth Orbit demonstrated that the attack of the space environment on spacecraft materials is more extensive and complex than originally imagined. While the space environments differ, depending on the orbital altitude, the following components are present in different concentrations in LEO, MEO, and GEO: energetic, charged particles; UV radiation; atomic oxygen; space debris and micrometeorite particles; and temperature fluctuations.

The survivability of spacecraft over the extended periods of time during which their critical components must operate within specific parameters requires materials that can withstand the degradation and erosion caused by the space environment, without producing excessive out-gassing. This can only be accomplished by a fundamental understanding of the complex reaction processes that occur when the materials are exposed *simultaneously* to the components of the space environment. Research that exposes materials to individual space components *sequentially* has produced erroneous results. For example, polysulphone exposed sequentially to electrons and atomic oxygen has an erosion rate more than an order of magnitude lower than that measured when both space environmental components are present simultaneously.

SECTION 19.10—STRUCTURES FOR SPACE

Highlights

- Space structures technologies produce lightweight, rigid structures to withstand the forces of launch and the rigors of the space environment, without out-gassing.
- The search for new materials will be aided by computational approaches for predicting the existence of multielement compounds that are suitable for space applications and provide the required properties. Research is needed to explore more efficient methods for organizing material systems' data by using artificial neural networks (ANNs).
- Composite isogrid components for missile and spacecraft structures will permit, for example, innovative launch vehicle interstages that reduce manufacturing costs and launch costs by reducing weight.
- Magnetohydrodynamic (MHD) micropumps with addressable shape memory polymer (SMP) valves can be fabricated for mass production and low-cost parts and then engineered into space structures.
- Technology developments that design, fabricate, test, and evaluate subscale, integrated electronics should result in at least a factor-of-two weight reduction for space electrical systems.

OVERVIEW

Space structures differ from their terrestrial counterparts. These (space) structures place a high premium on lightweight, very strong, rigid materials. They must withstand the forces of launch and insertion into orbit. Once in space, they must deploy and function properly for the life of the system. High levels of radiation, extremes of temperature and temperature gradients, impacts with space microparticles and atomic oxygen, and out-gassing characterize the space environment. Space structure technologies include the materials; the manufacture of the materials; the molding, machining, and other fabrication techniques; and the assembly operations. Some structures will be multifunctional, some will employ emerging technologies, and some will incorporate smart materials.

Space system structures include satellite bus structures, panels, tanks and piping, heat pipes, solar panel structural elements, and elements to connect, deploy, and operate satellite components. They also include structural elements, combustion chambers, nozzles, and coupling devices for launch vehicles. These structures must be lightweight, rigid, and stable because they must support all operations of the space system throughout its designed life. The structures must withstand the forces of launch and insertion into orbit; assist in deploying sensors, antennas, and other mechanisms; and then provide continuing stable physical support for the entire satellite. Launch vehicle structures must withstand similar stresses, plus the heat of propulsion, forces of separation, and, in case of reusable structures, multiple cycles. High-temperature combustion chambers and propulsion nozzles are critical to increasing launch vehicle lift capacity.

Developing space technologies include composite isogrid components for missile and spacecraft structures. New and innovative launch vehicle interstages that use the composite isogrid design and fabrication technology will be developed. The current payload fairings for the Titan, Delta, and Atlas launch vehicles are made from metallic isogrid stiffened structures that are costly to manufacture and require long lead time. Using composite isogrid structures can reduce fairing and interstage manufacturing cost by nearly a factor of 2 and reduce weight by 40 percent.

Smart materials will allow large deployable components (e.g., high-power spot-beam antennas, large solar panels supporting high-power satellites, and others) to be folded for launch and then deployed in space. These materials will reduce the need for the actuators and other mechanical systems that would have to be included in the space vehicle just to deploy or assemble subsystems in space. In addition, smart structures allow the damping of vibrations in the structures. The development, fabrication, attachment of components, testing, and preparation techniques for launch are critical technologies that support the use of these smart materials.

The search for new space materials will be aided by computational approaches that predict the existence of multielement compounds that are suitable for space applications and provide the required properties (e.g., stiffness-to-weight ratio) to be cost effective to use in space. Research is needed to explore more efficient methods for organizing material systems' data by using AANs.

Structures that seamlessly perform multiple functions are extremely useful in space. A straightforward example of a multifunctional structure is satellite panels, which also incorporate passive heat pipes and radiators not only to support electronic components physically, but also to carry away the heat they generate.

An emerging special case of this type of structure is based on new microtechnologies and nanotechnologies and on advances in lithography. MEMS and MOEMS include simple machines (e.g., accelerometers and optical sensors, on chip-sized substrates). Advanced lithography techniques allow these devices and analog, digital, and hybrid electronic systems to be integrated on one silicon substrate to develop complex micromachines. Structures containing or manufactured of massively parallel arrays of these simple or complex micromachines and nanomachines could be used to form panels of space systems. Some array elements would include optical and other sensors, others would include microfuel cells and nozzles, and others would include complex electronics and computer circuits. Such panels may actually form the bus structure and payload of small satellites, which would enable sensing, deciding, and positioning functions, including storage and expenditure of consumable supplies (e.g., fuel), to be built into the bus. Fabricated into standardized "smart bus" structures that contain compartments for additional specialized military payloads, these materials will enable new classes of small space systems.

Current spacecraft electrical systems involve thousands of feet of cables and numerous connectors to route the power, data transmission, and command, control, and ground planes around the structure. These conventional systems are heavy and require extensive touch labor to manufacture the spacecraft bus. Technology developments that design, fabricate, test, and evaluate subscale, integrated electronics should result in at least a factor-of-two weight reduction for space electrical systems. The goal will be a 70-percent weight reduction in electronic component enclosures and harnesses and a 25-percent increase in the mass fraction for an overall satellite.

One developing technology that will benefit space systems is the construction of a micropump system by using the concept of MHDs. An MHD micropump will generate continuous, reversible flow, with readily controllable flow rates. These micropumps can be placed at any position in the fluidic circuit as an element, and the combination of them can generate fluidic plugs and valves. Included is a system that has membrane valves, addressable by SMP, which need just one master solenoid valve (power source) to enable a truly compact system. A major advantage is that the valves can remain in position (open or closed) when no power is supplied, which greatly decreases power consumption. These micropumps can be fabricated by lithographic technologies and micromachining for mass production and low-cost parts, which can then be engineered into space structures.

LIST OF TECHNOLOGY DATA SHEETS
19.10. STRUCTURES FOR SPACE

DATA SHEET 19.10. COMPOSITE ISOGRID COMPONENTS

Developing Critical Technology Parameter	New and innovative launch vehicle interstages that use the composite isogrid design and fabrication technology will be developed for missile and spacecraft structures. This will reduce the manufacturing costs by a factor of 2 and the weight by 40 percent.
Critical Materials	Selection of the best composite lay-ups will be studied. These lay-ups have to meet the stringent space environment conditions and have the required strength for missile and spacecraft structural components.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology will spur many commercial applications for lightweight spacecraft and spacecraft components.
Affordability	Because of the weight and cost reductions for the basic process, this technology should significantly reduce the overall cost of launching any given payload.

BACKGROUND

Flight demonstration of a new and innovative launch vehicle interstages using the composite isogrid design and fabrication technology has been proposed. The current payload fairings for the Titan, Delta, and Atlas launch vehicles are made from metallic isogrid structures, which are costly to manufacture and require long lead time. Composite isogrid structures will reduce fairing and interstage manufacturing cost by nearly a factor of 2 and will reduce weight by 40 percent. These manufacturing cost and weight savings will reduce the cost of launching space payloads and enable the launch of heavier/larger payloads into higher orbits. These lightweight components will significantly impact the cost-effectiveness of future launches.

DATA SHEET 19.10. LIGHTWEIGHT MULTIFUNCTIONAL SATELLITE STRUCTURES

Developing Critical Technology Parameter	This technology development effort focuses on designing, fabricating, testing, and evaluating subscale integrated electronics structures and on fabricating and testing a demonstration integrated electronic structure that has at least a factor-of-two weight reduction in the electrical systems, including the housing and harnesses. The goal will be a 70-percent weight reduction in electronic component enclosures and harnesses and a 25-percent increase in the mass fraction for an overall satellite. Many material composite parameters and architectures will be evaluated, and a model component will be designed using newly developed lightweight composite materials.
Critical Materials	Developmental composite materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	If the goal of a 70-percent weight reduction in electronic component enclosures and harnesses and a 25-percent increase in the mass fraction for an overall satellite can be achieved, commercial firms will incorporate this technology into future satellite components.
Affordability	Weight reduction in cabling, connectors, and component enclosures can be used for higher capability payloads or space vehicles that are lighter overall, which should reduce overall cost per capability.

BACKGROUND

Current spacecraft electrical systems involve thousands of feet of cables and numerous connectors to route the power, data transmission, and command, control, and ground planes around the structure. These conventional systems are heavy and require extensive touch labor to manufacture the spacecraft bus. Technology developments that design, fabricate, test, and evaluate subscale, integrated electronics should result in at least a factor-of-two weight reduction for space electrical systems. The goal will be a 70-percent weight reduction in electronic component enclosures and harnesses and a 25-percent increase in the mass fraction for an overall satellite.

DATA SHEET 19.10. SPACE MATERIALS DEVELOPMENT VIA NEURAL NETWORKS

Developing Critical Technology Parameter	This developmental technology focuses on a computational approach for predicting the existence of multielement compounds that are suitable for space applications and provide the required properties (e.g., stiffness-to-weight ratio) to be cost effective for use in space. This research will address and explore more efficient methods to organize material systems data using both supervised and unsupervised ANNs. This includes mapping structure properties, processing procedures, and use conditions. The fundamental equations of the quantum mechanic properties for solids are well established and will be numerically solved in this study—solved at least, in a reasonable approximation by means of "first-principles-based" methods developed over the last decade.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computational algorithms to solve numerically the fundamental equations of quantum mechanics for solids.
Major Commercial Applications	The commercial market will immediately benefit from this research effort because there is a direct one-to-one correlation of this effort to commercial space structures benefits.
Affordability	While the research work will involve costs, it may lead to higher strength, lighter, and more suitable materials for space structures, which should then lead to longer on-orbit life, less costly access to space, or other advantages in space systems.

BACKGROUND

Material design efforts depend critically upon amassing large volumes of experimentally determined data that permit an individual to perceive an underlying pattern not previously apparent. However, even with great insight and the advent of "combinatorial chemistry," billions of potential material systems have to be considered.

A clear motivation exists to use computational methods to solve problems because the costs of computational services has been reduced drastically and the costs of experimental research has increased steadily in recent years. The approach for this research is a materials design and/or discovery approach that exploits science-based models validated with a minimum number of experiments.

As elemental and compound materials data have become more prevalent, so has the impetus to develop accurate and expeditious methods of predicting the compound properties. Computing technology and the web-based group of informed and innovative scientists who are actively interfacing with an ever-widening community are driving this evolving but converging focus on methods.

One should note that multiple stoichiometries enable billions of compounds to be formed. However, the practical and useful limit is probably still more like a few million. By combining the number of prospective compounds and solutions having distinct properties required for space, the total number of useful material systems, although still very high, could be reduced to a manageable and computatable list. In view of these considerations, a direct computational approach for predicting the properties of bulk macroscopic matter is generally not practical. Clearly, those physical properties dependent upon integrals of long-range correlation functions cannot be calculated with sufficient accuracy nor can dynamical properties be calculated from correlation functions that exhibit long-time constants.

DATA SHEET 19.10. SHAPE MEMORY POLYMER/MAGNETOHYDRODYNAMIC (SMP/MHD) MICROFLUIDIC SYSTEMS

Developing Critical Technology Parameter	This developing technology will focus on constructing a micropump system using the concept of MHD. An MHD micropump will generate continuous, reversible flow, with readily controllable flow rates. By mismatching the electrodes, a swirling vortex flow can be generated for potential mixing applications. No moving parts are necessary, and the dead volume is minimal in design. These micropumps can be placed at any position in the fluidic circuit as an element, and the combination of them can generate fluidic plugs and valves. Included is a system that has membrane valves, addressable by SMP, which need just one master solenoid valve (power source) to enable a truly compact system. The technical goals will involve conducting a detail study of the scalability of MHD toward microsystems. Studies will calculate the pressure required to deflect the membrane in both phases of the SMP to enable a valving manifold system that can supply and control the appropriate pressure. A generalized fluidics system with multiple valves and flow channels is the eventual goal.
Critical Materials	SMP fluidics valving systems; SMP membranes that can be heated individually.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Microfluidics is the field of manipulating fluids in micromachined channels. The ultimate goal is to integrate pumping, valving, mixing, reaction, and detection on a chip for biotechnological, chemical, environmental, and health care applications.
Affordability	The benefits of this technology may be multifunctional structural elements in space systems. If such structures also serve as cooling fluid or fuel conduits, for example, more mass/space could be devoted to the payload of interest or significantly reduced costs could result because of the decreased mass.

BACKGROUND

The construction of a micropump system using the concept of MHDs is one developing technology that will benefit space systems by reducing weight. An MHD micropump will generate continuous, reversible flow, with readily controllable flow rates. These micropumps can be placed at any position in the fluidic circuit as an element, and the combination of them can generate fluidic plugs and valves. Included is a system that has membrane valves, addressable by SMP, which need just one master solenoid valve (power source) to enable a truly compact system. A major advantage is that the valves can remain in position (open or closed) when no power is supplied, which greatly decreases power consumption. These micropumps can be fabricated by lithographic technologies and micromachining for mass production and low-cost parts, which can then be engineered into space structures.

An MHD micropump will enable a truly integrated microfluidics system as a compact propulsion element for biomedical analysis instrumentation or biotechnology processing systems. A microfluidics valving manifold system is critical to all total analysis systems.

This technology will help us determine the conductivity required by the pumped fluid to prevent electrolysis and the magnetic fields and electrical currents required at a microscale micropump.

SECTION 19.11—INTEGRATED SYSTEMS

Highlights

- Since many other space technologies now allow longer-life space systems, designers will probably not anticipate all the possible uses that those systems could support before the ends of their usable lives.
- Standards, modular design, reprogrammability and reconfigurability from the ground, and other technologies will enable existing in-space systems to be adapted to new missions.
- Software technologies focus on domain architectures, protocol architectures, data-driven run-time dispatch, introspective languages, multiple run-time versions of modules, and agenda architectures.
- Technology that allows the use and reuse of space systems in different array configurations will enable long-lived space military systems.
- Technology that supports modular construction and the interchange of modules in existing space systems will become more important.

OVERVIEW

This section discusses various technologies that enable the flexible use and reuse of space assets. Since many other space technologies now allow longer-life space systems, designers will probably not anticipate all the possible uses that those systems could support before the ends of their usable lives. Technologies that adapt, modify, and upgrade existing space assets for new or changed applications will become increasingly important. Together with reprogrammability and reconfigurability from the ground, upgrades of hardware modules will allow the use of existing "space infrastructure" in new ways as technologies emerge.

Space technologies for power generation, propulsion, reliable operation, and so forth are increasingly long lived in the space environment. This enables space systems to remain on orbit for greater periods of time. These systems are costly to build, to boost into orbit, and to continue to operate, and the lead times from concept to on-orbit capability are long. In essence, obsolescence in space, because of excellent system/component reliability and service life, is a future design criterion. The end result is that the military is interested in systems integration technologies that will enable getting new capabilities into space more quickly and at less cost. These include standards, modular design, reprogrammability and reconfigurability from the ground, and other technologies that will enable existing in-space systems to be adapted to new missions (some not conceived in the original system design).

Developing software technologies focus on domain architectures, protocol architectures, data driven run-time dispatch, introspective languages, multiple run-time versions of modules, and agenda architectures. The payoff is the ability for software systems to adapt (i.e., self-modify behavior) to meet a constant stream of new requirements long after deployment. This capability is particularly beneficial to space systems, which have 10–15 years of life but cannot be accessed easily when changes are required.

Also important are technologies that effectively support the evolution of software by preserving design information, by developing and tying architecture and code so they evolve together, by tracking dependencies as assumptions change, and by retesting only the affected portions of the system. This developing technology area will enable the continuous evolution of families of long-lived, software-intensive space systems that have incremental evolution costs proportional to the size of the change and not to the size of the system.

Finally, technologies that support the interchange of modules in existing space systems will become more important. These include space tug technologies, standardized payload modules and standardized electrical modules and interfaces, and technologies that enable the replacement of modules in space. Together with reprogrammability from the ground, the upgrades of hardware modules will allow use of existing "space infrastructure" in new ways as technologies emerge. The goal is seamless transition of large constellations and clusters to meet new mission requirements or provide updated capability without abandoning on-orbit resources and launching entirely new constellations.

LIST OF TECHNOLOGY DATA SHEETS
19.11. INTEGRATED SYSTEMS

DATA SHEET 19.11. FIELD-ADAPTABLE SYSTEMS TECHNOLOGY (FAST)

Developing Critical Technology Parameter	This developing technology focuses on domain architectures, protocol architectures, data-driven run-time dispatch, introspective languages, multiple run-time versions of modules, and agenda architectures. The payoff is the ability for software systems to adapt (i.e., self-modify behavior) to meet a constant stream of new requirements long after deployment. This capability is particularly beneficial to space systems, which have 10–15 years' life but are not accessible for change.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	The software being developed under this technology area will have to replan and reschedule different component selections and respond to changes in resource availability. The software will need to respond to unexpected situations and opportunities in seconds instead of days or months. Evaluators will automatically determine when change is needed, and performance will be improved by tailoring the response to actual data at run time. To respond in more than one way to any given set of conditions or inputs, new run-time support architectures need to be developed with entire software component repositories in running code, along with the descriptions of the components and the ability to select components at run time. Metrics will be developed to measure and test software adaptability and robustness. The adaptive mechanisms will be tested to determine any loss of performance. Metrics based on coverage of space of inputs and conditions will be developed and standard optimization techniques such as caching and evaluation will be used.
Major Commercial Applications	This technology will enable adaptive systems to learn from their own mistakes, from user instructions, and from other adaptive systems. Many commercial applications could use this technology.
Affordability	This technology will be very affordable once it has been developed.

BACKGROUND

Today's systems must respond to rapid changes; however, current software cannot easily accommodate changes other than those envisioned by the original designer. Revision involves expensive human intervention and growth in complexity of original code and design and cannot happen in real time.

In the past, requirements were fixed, designers were generally not involved in maintenance, and design information was routinely discarded. The FAST program provides the technology that will effectively support software evolution by providing for swifter response, improved performance, and ease of update.

The FAST developing technology needs to be pursued concurrently with small-scale feasibility demonstrations. A series of experiments will provide proof of concept of this technology. The demonstrations will show systems undergoing a particular change or set of changes aided by the application of adaptive and evolutionary development technologies emerging from this program. These technologies focus on domain architectures, protocol architectures, data-driven run-time dispatch, introspective languages, multiple run-time versions of modules, and agenda architectures. The software will be able to respond to unexpected situations and opportunities in seconds instead of days or months, evaluators will automatically determine when change is needed, and performance will be improved by tailoring response to actual data at run time.

DATA SHEET 19.11. SMART SOFTWARE FOR AUTONOMOUS OPERATIONS

Developing Critical Technology Parameter	This effort will provide the technology that effectively supports software evolution by preserving design information, by developing and tying architecture and code so they evolve together, by tracking dependencies as assumptions change, and by retesting only the affected portions of the system. This developing technology will enable the continuous evolution of families of long-lived, software-intensive space military systems that have incremental evolution costs proportional to the size of the change and not to the size of the system. This is needed to continue the development of space asset autonomy.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Developing software that can evolve.
Major Commercial Applications	This technology will improve commercial “smart systems” in general—not just for space autonomy.
Affordability	This technology will reduce costs of systems on orbit and enable modifications and upgrades to extend their lives.

BACKGROUND

The objective of this technology effort is to provide the necessary R&D to support a series of small-scale feasibility demonstrations. For these demonstrations, small vignettes of current systems will undergo a particular change or set of changes aided by the application of software engineering and development technologies emerging from this program. These emerging technologies focus on requirements and rationale capture, rapid prototyping, architecture-centric development, advanced testing and analysis, reengineering, information management, and dynamic language implementations. The payoff is the ability for software systems to evolve (i.e., to be upgraded) to meet a constant stream of new requirements long after deployment.

Current technology does not easily allow for changing requirements. In the past, requirements were fixed, designers of software were generally not involved in maintenance, and design information was routinely discarded. This effort provides technology that will effectively support software evolution by preserving design information, by tying architecture and code so they evolve together, by tracking dependencies as assumptions change, and by retesting only the affected portions of the system. This developing technology area will enable the continuous evolution of families of long-lived, software-intensive space systems that have incremental evolution costs proportional to the size of the change and not to the size of the system.

DATA SHEET 19.11. SPACE AUTONOMOUS OPERATIONS AND AUTOMATED SERVICING TECHNOLOGIES

Developing Critical Technology Parameter	Critical technology developments will be pursued to enable autonomous satellite operations and automated, on-orbit servicing, including: • General navigation and communications, attitude determination and control, and proximity operations software and sensors that allow centimeter-level autonomous rendezvous and control of spacecraft (supervised and unsupervised) • Automated fault-detection, isolation, diagnostic, and correction software and systems • Fault-tolerant grappling and physical connection/deconnection systems • "Plug and stay" and other accessible and replaceable architectures for operational resource units (ORUs) in electronics, power generation and control, thermal dissipation systems, antennas, sensors, and instrumentation • Connectorless transfer of information and power between spacecraft • Low-leakage refueling technologies • Fault-tolerant computing and software architectures that allow continuity of operations and processing through multiple hardware and software failures.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Robust software for fault-tolerant computing; algorithms for keep-out control; proximity operations; autonomous command, control, communications, computers, and intelligence (C4I); accurate attitude control, guidance, navigation.
Major Commercial Applications	This technology is particularly applicable to satellite fleet operations: geosynchronous communications, little and big LEO constellations, and commercial imaging.
Affordability	Nonrecurring expenses for autonomous operations will be justifiable by the significant reduction in overall system life-cycle costs and risk.

BACKGROUND

The ability to extend the life of spacecraft without the need and tremendous expense of manned repair missions is required. Primary military benefits from these technologies will be twofold: a reduction of overall mission cost through spacecraft lifetime extension and operations cost avoidance and an increase in mission scope and effectiveness.

This developing technology will enable the continuous evolution of families of extended lifetime space systems. Autonomous operations of space systems lessen and/or eliminate the need for extensive continuous mission planning, command and control (C2), and payload data reduction on the round, which may account for approximately 40 percent of the system life-cycle cost.

By increasing the fault tolerance of the spacecraft, the expected operational lifetime can be extended. A revolutionary strategy of on-orbit servicing, ORU replacement, and upgrade of payload and systems capability would enable failed systems to be serviced and repaired and/or replaced. Perhaps of greater importance, an on-orbit ORU replacement capability allows technology and system upgrades to occur over time. This enables new instruments and capabilities to be employed selectively, without invoking the costs associated with entire new spacecraft development. Thus, much as avionic suites can be upgraded to allow mission electronic evolution in aircraft, satellite missions can be also extended or evolved over time.

These technologies will enable a service satellite to dock autonomously with a host satellite and provide to this satellite its fluids, sensors, and other replacement components. These technologies will also allow proximity to provide such functionality as automated damage inspection and debris collection.

DATA SHEET 19.11. INTEGRATED COMMUNICATIONS/ CONTROLLER TECHNOLOGIES

Developing Critical Technology Parameter	The objective of this developing technology is to provide a wideband in-theater communications backbone.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial applications of this technology exist for local area networks (LANs) where two-way radios and so forth are not suitable (e.g., in mountainous terrain search and rescue work).
Affordability	Final equipment costs should be comparable with current state-of-the-art programmable, multiband transceivers.

BACKGROUND

This developing technology will demonstrate LOS, regional beyond-line-of-sight (RBLOS) or air-to-air, beyond line-of-sight (BLOS), or SATCOM and will broadcast or multicast information flow through an airborne surrogate satellite. An integrated communications package will be fabricated and demonstrated from an airborne platform. The airborne communication equipment will include new wideband programmable data links, lightweight programmable radios, a communications controller, and a communication switching system. The services that this technology provides include relay and/or dissemination of voice, C2 data, and imagery data [video, electro-optical (EO), IR, or SAR].

DATA SHEET 19.11. SATELLITE AND GROUND SYSTEM SIMULATION

Developing Critical Technology Parameter	This technology development will use software modeling to create affordable, reusable emulations of satellites, satellite subsystems, and ground antennae. The simulator will be able to model the characteristics of a wide variety of space vehicles, allowing the models to be configured for a given satellite configuration via a relational database. High data rates, encryption, constellation management, spacecraft processor simulation, application program interfaces to satellite factory software will be investigated.
Critical Materials	None.
Unique Test, Production, Inspection Equipment	Simulators use COTS PC technology, with unique protocol generation and decommutation provided by COTS communications modules at the plug-in board level.
Unique Software	Next-generation systems will use expert systems, integrated instructional aids, visualization, and unique payload modeling. Eventually, simulations will be on board to support autonomous operations.
Major Commercial Applications	This technology can be used for system integration, system tests, conceptual modeling, mission planning, training, and rehearsals for satellite system operators and analysts.
Affordability	Sophisticated simulators can reduce system integration cost, schedule, and risk, reduce time to train, and provide procedural and anomaly correction validation before application to expensive program assets.

BACKGROUND

Conventional simulations for satellite programs use one-of-a-kind, satellite-specific emulations developed for a given space vehicle program. Simulation software is expensive to develop and test, difficult to maintain, and inflexible for emulating anomalous conditions or supporting multiple stages of the space vehicle lifetime. Program-specific or program-developed satellite simulations are typically not available to all aspects of a program (e.g., ground system integration, crew training) until the space vehicle has been completed and is ready for launch, thereby stretching program deployment schedules.

This program will investigate innovative, high-fidelity PC-based simulation systems that can be introduced into all areas of satellite programs at early stages. Development of satellite or subsystem databases can proceed in an incremental manner according to the program requirements and schedule. Configuration of the simulator via the relational database eliminates expensive software development and maintenance costs unique to each program. Satellite- and ground-antenna simulation will allow closed-loop test and training scenarios, without use or expense of valuable real-world assets.

SECTION 19.12—SPACE-BASED LASERS (SBLs)

Highlights

- Space communications with high-bandwidth laser links will greatly increase the use of lasers on satellites.
- Using sophisticated detection and imaging that employ laser systems for target illumination, acquisition, and tracking will significantly increase space platform laser applications.
- Laser beams, because they travel at the speed of light and have such a narrow wavelength bandwidth, are finding more applications in space for surveillance and tracking in situations where discrete frequencies are required to provide high S/N ratios. Laser tracking permits target position to be determined more accurately and faster.
- Microlaser and nanolaser technology is beginning to find applications in control modules and guidance systems for space missions and satellites and will have a major impact as on-chip lasers are developed and become qualified for space applications.
- Short-to-mid-IR wavelength (high-energy) lasers, including X-ray (γ-ray) lasers, are potential sources for space weapons and are being considered for applications against missiles and other targets of interest.
- High-energy SBLs are being developed to provide wide-area illumination for surveillance.
- High-power SBLs weapons are envisioned for use in strategic scenarios from space platforms.
- Laser uplinks/downlinks are being developed for future satellite communication applications.

OVERVIEW

Lasers are used in many space applications, ranging from microlasers for on-chip applications, to laser diodes in electronic components, to laser communication modules, to large laser diode arrays for surveillance or as pump sources for other solid-state lasers, to high-energy lasers for possible weapons applications. This section outlines technologies applicable to the development and production of SBLs and laser systems in the IR visible and UV regions of the electromagnetic (EM) spectrum from 0.01 μm to 30 μm.

This section identifies developing SBL technologies that could have a significant impact on future DoD space systems. This includes major improvements in lasers applicable for space (in terms of weight and efficiency); the development of significantly new cost-saving design, fabrication, and support technologies for the generation of both low- and high-power coherent radiation sources for space applications; the development of microlasers and nanolasers for space MEMS and MOEMS applications; and the expansion of the laser operability range to shorter wavelengths (including X-rays and the γ-ray regime) and smaller dimensions (including microchip- and nanochip-level lasers). Lasers can operate in a continuous, repetitive pulse, repetitive burst mode or in a single-pulsed mode, depending on the application and requirements. Laser systems sometimes incorporate components such as amplifier stages, frequency conversion components, Raman cells, multiple wave mixing components, or other major elements in addition to the laser oscillator. This section covers HEL[5] and low-energy laser (LEL) systems.

The National Research Council's report, "Harnessing Light: Optical Science and Engineering for the 21st Century," dated 1998, is a comprehensive study by national experts in various fields of optics. The report states:

> Throughout history, new technology has had a profound effect on how wars are conducted. Usually, the victors were those best able to apply the new technology. Over the course of the past 50 years, nuclear weapons, microwave radar, guided missiles, and other developments have led to major realignments of

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[5] Section 11 addresses HELs being developed for terrestrial applications. This section (Section 19) addresses only space-unique laser technologies.

> defense strategy. Today, the traditional modern strategy of massing large numbers of military personnel and materiel to engage enemy forces is giving way to high-tech methods of conducting warfare that minimize casualties. The U.S. military mission now requires a versatile fighting force capable of both conventional field and urban warfare in a global venue. To improve the effectiveness of the combatant while reducing casualty rates, the military has a number of efforts under way that include reliance on speed and stealth to overcome opposing forces; a better equipped land warrior; rapid detection and control of nuclear, chemical and biological threats; and dissemination of real-time intelligence on enemy targets.

Optics and lasers play a key enabling role in these plans. In the future, lasers and laser optics will be the basis for entirely new classes of space defense applications that will change yet again the way in which wars are conducted.

LIST OF TECHNOLOGY DATA SHEETS
19.12. SPACE-BASED LASERS (SBLs)

DATA SHEET 19.12. SODIUM HIGH-ENERGY LASER (HEL)

Developing Critical Technology Parameter	This developing technology will provide high-quality, kilowatt-class laser sources in the wavelength range from the near UV to the far IR. A variety of nonlinear optical processes that convert the output wavelength of a diode-pumped solid-state laser to a variety of fixed and variable wavelengths will be investigated. Theoretical and experimental studies of the gain and noise characteristics of parametric processes in mode-locked laser pulse trains will be performed. The results of this and previous research will be incorporated into the system design and performance analysis models for laser devices that use multiple parametric processes.
Critical Materials	Nonlinear optical materials that will increase conversion to the visible by an order of magnitude.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Many applications could benefit if most of the goals are achieved. The most promising application is satellite laser communications.
Affordability	The development costs should be offset during system life cycle if the improvements in efficiency can be obtained.

BACKGROUND

A novel laser system that produces yellow light at one of the sodium D lines was built and demonstrated. The system uses a solid-state laser that produces a diffraction-limited, 20-W beam with a special pulse format. The pulse format was designed to optimize the return from a laser guidestar beacon that will be created in the mesospheric sodium layer of the earth’s atmosphere. The laser wavelength was converted from near-IR to yellow using a special high-power nonlinear optical subsystem. Currently, the system currently operates at a 15-percent conversion efficiency.

In the near term, a high-power sodium wavelength laser will be developed as a source for creating an artificial reference star (laser guidestar) in the mesospheric sodium layer of the earth’s atmosphere for the GBL and space surveillance projects. Multiple parametric processes will be used to convert radiation at 1,064 nm to 589 nm. This technology program has goals of achieving 200 W and 25-percent conversion efficiency. In parallel with this effort, mechanisms for producing near UV to far IR sources will be investigated for use in ultrasensitive remote-sensing and aircraft self-protection systems. The goal of this effort is to produce an operational kilowatt-class, frequency-agile source by 2005.

DATA SHEET 19.12. ULTRASTABLE LASER TECHNOLOGY

Developing Critical Technology Parameter	This technology development program consists of an effort to develop ultrastable laser sources with the capability of operating at the selected wavelengths required for space applications. It will experimentally investigate and optimize novel techniques to improve the performance of, or create, laser devices that have selected operating characteristics for space environments. For example, ultrastable lasers and lasers operating at selected short wavelengths have potential applications in fields as diverse as highly accurate clocks/frequency standards and space communications. In addition, high-power near/mid-IR lasers are well suited for applications as illuminators and as certain countermeasures.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Many of these technology attributes will have impact on the commercial laser market. It is difficult to say with certainty which ones and to what extent at this point in the research effort.
Affordability	It should produce a much more cost-effective product. A lot of the cost savings is in the efficiency and compact packaging technologies being developed.

BACKGROUND

This technology program is designed to develop high-efficiency, frequency-agile, scalable, solid-state lasers for space missions and to develop the technology to extend laser operating lifetime to greater than 10 years. This effort study the effects of the space environment on laser performance to spur the development of compact, lightweight, high-power, high-efficiency SBLs that can withstand this environment.

This technology effort has also established a program to implement birefringence compensation, which is needed to improve injection laser efficiency and should produce higher output powers.

DATA SHEET 19.12. FREQUENCY-AGILE HIGH-ENERGY LASERS (HELs)

Developing Critical Technology Parameter	This developing technology will provide high-quality, kilowatt-class laser sources in the wavelength range from the near UV to the far IR. A variety of nonlinear optical processes that convert the output wavelength of a diode-pumped solid-state laser to a variety of fixed and variable wavelengths will be investigated. Theoretical and experimental studies of the gain and noise characteristics of parametric processes in mode-locked laser pulse trains will be performed. The results of this and previous research will be incorporated into the system design and performance analysis models for laser devices that use multiple parametric processes.
Critical Materials	Nonlinear optical materials that will increase conversion to the visible by an order of magnitude
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Many applications could benefit if most of the goals are achieved. The most promising application is satellite laser communications.
Affordability	The development costs should be offset during system life cycle if the improvements in efficiency can be obtained.

BACKGROUND

In the near term, a high-power sodium wavelength laser will be developed as a source for creating an artificial reference star (laser guidestar) in the mesospheric sodium layer of the earth's atmosphere. Multiple parametric processes will be used to convert radiation at 1,064 nm to 589 nm. This technology program has goals of achieving 200 W and 25-percent conversion efficiency. In parallel with this effort, mechanisms for producing near UV to far IR sources will be investigated for use in ultrasensitive remote-sensing and aircraft self-protection systems. The goal of this effort is to produce an operational kilowatt-class, frequency-agile source by 2005.

DATA SHEET 19.12. INFRARED HIGH-ENERGY LASER (IR HEL) FOR SPACE SURVEILLANCE AND COUNTERSPACE (CNT)

Developing Critical Technology Parameter	The goal of this technology effort is to provide a 10-kW IR space-qualified prototype laser device within 5 years. This research and technology development will allow the scale-up of power output of diode-pumped, solid-state (crystalline or glass) lasers; investigate diode-pumped, fiber optically pumped semiconductor lasers; investigate approaches to make these systems frequency agile (multicolor); and investigate the ability to package and field these demonstrator systems. Scaling efforts of the solid-state lasers will extend the power of these systems to tens of kilowatts and beyond. Scaling efforts for the lower power systems includes coherently coupling the outputs of many smaller, highly efficient lasers. This R&D will provide the most advanced diode-pumped, solid-state laser brassboards currently available. It will leverage commercial technology developments for precision laser machining and future semiconductor photolithographic techniques.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology will provide the most advanced diode-pumped, solid-state lasers currently available. Leveraging commercial technology developments for precision laser machining and future semiconductor photolithographic techniques with this developing technology will provide a much superior product than that which is currently available to the commercial world.
Affordability	This technology should provide a cost-effective product and provide reduced logistical support in these space assets, reducing the overall cost significantly.

BACKGROUND

This developing technology will enable initial studies that actively track satellites using coherent radiation. It will also be used by adaptive optics systems to make atmospheric corrections to images of space objects.

DATA SHEET 19.12. HIGH-EFFICIENCY, COMPACT, 1,550-nm SEMI CONDUCTOR SPACE COMMUNICATION LASER DIODE ARRAYS

Developing Critical Technology Parameter	This developing technology will research high-power, high-beam-quality semiconductor laser-based devices to develop suitable device structures that enable compact, rugged, high-power lasers for space communication systems and provide optical pump sources for the next-generation air and space weapons. The near-term goal is to develop a CW diffraction-limited, single-element device at 1,550 nm and a 100-W coherent array demonstrator. The far-term goal (2004) is to demonstrate a 1,550-nm laser of several kilowatts. This developing laser structure technology effort will include near-IR single-device power scaling, fiber laser development, and coherent diode array development. These projects are interrelated and build upon one another. The thrust of the research on semiconductor lasers focuses on designing laser devices, collecting experimental performance data on these devices, and modeling new promising laser devices at various wavelengths. The research on fiber lasers will be performed in the physical output power limitations of a single, rare-earth, doped fiber. Semiconductor lasers and fiber lasers are lightweight, compact, efficient, and rugged.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology offers many potential applications once developed. The area of satellite communications is a prime candidate. However, other applications, such as mast lighting, will benefit.
Affordability	This technology should be quite cost effective when efficient sources are developed.

BACKGROUND

This developing technology application project includes the development of high-power semiconductor lasers that will be required for two specific projects:

- The single-device power-scaling project entails the R&D of extremely bright, high-power lasers and amplifiers in the GaAs and InP material systems. Single devices are immediately spun off into customer applications projects with U.S. Government organizations to field prototype systems for very-near-term applications. Single-laser diode devices are also transitioned into laser bars that contain multiple diode elements, which are extremely effective for pumping fiber lasers.
- The Array Technology project investigates and develops technologies that enable the fabrication of coherent semiconductor and fiber laser/amplifier arrays using a master oscillator, power amplifier configuration. The outputs of the amplifiers are phase-adjusted to produce a coherent output beam that produces a beam intensity much higher than that of an incoherent beam. This multiyear program pushes semiconductor laser technology to higher output powers while maintaining very high beam quality. Contractual efforts and a strong in-house research program provide a state-of-the-art technology base for understanding phenomena limiting semiconductor laser performance.

DATA SHEET 19.12. ULTRASTABLE LASER-DIODE SPACE-TRACKING ARRAYS

Developing Critical Technology Parameter	This technology development program will experimentally investigate and develop novel techniques to enhance the performance of, or develop new, ultrastable laser devices that will be able to operate at selected wavelengths of military significance. These laser devices are required as pump sources to achieve additional operating wavelengths. Current efforts have produced several improvements in laser stabilization, new CW laser wavelengths and powers, and lightweight system packaging. This developing technology effort will produce laser systems that have world-record (38 W) CW outputs and can operate at selected wavelengths in the 3–4 μm wavelength range.
Critical Materials	High-purity, high-efficiency new laser-diode source materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Many commercial applications could result once this technology is developed. These include high-efficiency laser welders, laser eye-surgery equipment, and many other laser diode applications.
Affordability	This technology should be very cost effective once initial development technology is complete.

BACKGROUND

Ultrastable lasers and lasers operating at selected short wavelengths have potential applications in fields as diverse as highly accurate clocks/frequency standards, communications.

This technology program consists of an in-house effort to develop ultrastable laser sources with the capability of operating at selected wavelengths. Often, these devices find use as pump sources to achieve additional operating wavelengths. Past efforts produced several improvements in laser stabilization, new CW laser wavelengths and powers, and system packaging.

This program includes the establishment of a national laser stabilization laboratory to generate high-accuracy laser clock technology for the next-generation GPS systems.