Crosslink®

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Summer 2009

Developing Responsive and Agile Space Systems

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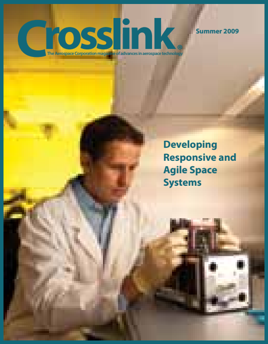

On the cover: Petras Karuza, Mechanics Research Office, installs the electronics core into the Pico Satellite Solar Cell Testbed nanosatellite. The core contains everything the nanosatellite needs: solar array and battery management, flight computer, inertial measurement unit, radio, camera controller, and an experiment controller.

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From the Editors

The term "agile space" stems from a growing consensus within the space community that the United States must be able to field certain classes of space systems more rapidly and flexibly. To help realize this goal, the DOD established the Operationally Responsive Space (ORS) Office in May 2007; its goal is to identify and address technological issues that will enable a more timely delivery of space-based services to meet warfighter needs.

The ORS Office has devised an end-state architecture and is identifying the technologies that will enable its realization. Aerospace has been contributing to the definition and execution of this architecture, which encompasses all aspects of space systems—launch, space, and ground. Articles in this issue of *Crosslink* review the various components of this architecture and the progress that has been made toward implementing and coordinating them.

It is important to note that the ORS Office is not in competition with major space programs; rather, it is an adjunct to those programs and the systems they support. Its immediate focus is on the application of space power to the tactical theater. That includes devising new concepts for developing and deploying satellites, but it also entails exploiting existing space systems and infrastructure to achieve tactical demands with greater speed and versatility.

The ORS Office is not the only—nor the first—organization to pursue agile space concepts. The DOD's Space Test Program (executed by the Space and Missile Systems Center) and the Air Force Research Laboratory have a history of developing and launching small experimental satellites quickly and efficiently. Satellites developed by these programs have acquisition schedules that are typically three to four years—significantly shorter than for major space programs. Notably, these organizations have supported Aerospace in the development of picosatellites and CubeSats, which have demonstrated enabling technologies and provide one possible model for rapid system integration.

The ORS Office was established in Albuquerque to take advantage of the expertise developed by the Space Test Program and Air Force Research Laboratory, which also reside there. It is hoped that these three organizations can collectively improve acquisition timelines and apply their research expertise to operational systems. As the articles in this issue demonstrate, Aerospace has extensive experience in facilitating cross-program efforts and architectures and assessing the potential of new technologies. As such, the corporation is well positioned to help achieve the ambitious goals of agile space.

Hyperspectral Imager Detects Mineral Deposits

Dean Riley and Mike Martino (third and fourth from left) with the pilots of the Twin Otter aircraft in which the SEBASS instrument was installed.

Aerospace recently completed its largest hyperspectral survey to date using the SEBASS (Spatially Enhanced Broadband Array Spectrograph System) airborne sensor. The Northern Quebec Survey Team, part of the Spectral Applications Center in Chantilly, Virginia, conducted an extensive survey in the fall of 2008 to look for precious metal deposits in an 860,000-acre area just south of the Arctic circle near Hudson Strait.

The survey was conducted for Goldbrook Ventures, a Canadian mining company that owns approximately half the acreage along the Raglan Belt, a mining district known for its nickel-sulfide deposits; some of the surface rocks in this region are more than 3 billion years old.

SEBASS is a pushbroom hyperspectral imager that is mounted aboard a Twin Otter airplane and flown over the region of interest. For the Northern Quebec survey, SEBASS data was merged with LIDAR data and shortwave hyperspectral sensor data. A schoolroom in a tiny Inuit village near the survey site was used as an ad hoc office to process the data.

"Northern Quebec is just one of many survey areas conducted through Aerospace's close collaboration with our commercial client, SpecTIR LLC in Reno, Nevada," said Karen Jones of Civil and Commercial Operations. "SpecTIR and Aerospace have complementary sensors—our SEBASS captures mid- to long-wave infrared spectral measurements within the thermal emissive range, and SpecTIR's ProspecTIR sensor captures the very near to shortwave infrared. Our combined sensors provide an unrivaled full spectral hyperspectral capability," she said.

The survey revealed an extensive nickel deposit, which was subsequently confirmed by drilling on the ground. This deposit, known as the Mystery Prospect, is now in the early stages of development. Niel Schulenburg, associate principal director for Advanced Sensor Applications, noted, "The team covered more than 1700 square kilometers in the airborne SEBASS survey. To meet the customer coverage requirements, the team members had to significantly modify their mission planning tools and collection operations, and they were very successful. This effort gives us confidence in conducting these types of large-area surveys in remote locations for other commercial clients."

Mission Assurance for Nuclear Security

The Aerospace Corporation has established a new Nuclear Operations Directorate to support the Air Force Nuclear Weapons Center and Air Force Space Command. Aerospace was brought in to assist these organizations after a number of high-profile lapses in nuclear security (by other organizations) came to light last year, including the flight of live warheads across the country and the shipment of nuclear fuses overseas.

"Initially, our focus was on identifying any issues not uncovered by the various commissions reviewing U.S. nuclear operations," said David C. Evans, who heads the new directorate. "The emphasis has begun to shift toward establishing processes to prevent recurrence of the issues uncovered and development of metrics to measure the health of the weapon system."

Aerospace has established a team—led by William Ballhaus, former Aerospace president and CEO—to conduct two mission assurance reviews annually. The first review, in August 2008, examined how the various organizations at Hill Air Force Base in Ogden, Utah, support the Minuteman weapons system as well as the role and effectiveness of the government and contractor team. Results from that review played a role in the decision to stand up Air Force Global Strike Command, which will be responsible for both ICBMs and bombers with a nuclear mission. The second review, completed in May 2009, added the topic of nuclear surety (i.e., safety and security) and assessed the practices of the ICBM System Program Office, Air Force Space Command, and various organizations at Kirtland Air Force Base in Albuquerque, New Mexico.

Evans suggests that many of the problems in nuclear operations have their roots in the same elements that caused the multitude of launch failures at the end of the last decade. "In ICBMs, like space, the weighting of the three program management elements went from technical, schedule, and then cost to cost, schedule, and then technical as budgets were cut. Decision makers seem to have overlooked the fact that nuclear operations have zero tolerance for error, and the performance standard is perfection," he said.

Aerospace has a rich history of support to the nation's ICBM arsenal, dating back to the corporation's founding in 1960. But, says Evans, Aerospace was selected for this assignment based on its demonstrated expertise in mission assurance and the ability to find the root cause of problems. "Minuteman is not a very complex system, but it is extremely intricate due to the number of interfaces and the interrelationship of system components and processes," he said. "That is what mission assurance is all about—understanding the interfaces and interdependencies."

Evans hopes to see a return to the discipline that was the hallmark of the Strategic Air Command. "I'm not saying we need to go 'back to SAC,' but everyone—military and contractor—needs to regain the discipline to say 'no' if saying 'yes' would result in a performance standard of less than perfection," he said.

AeroCube-3 Takes Flight

The Aerospace Corporation's third CubeSat, AeroCube-3, was launched from Wallops Island, Virginia, on May 19, 2009, as a secondary payload on the TacSat-3 mission. The picosatellite measures 10 × 10 × 10 centimeters and weighs about 1 kilogram, in keeping with the CubeSat specification. It is more complex than its two predecessors and has several improvements; most notable is the new solar power subsystem that replaced the one that failed on AeroCube-2. AeroCube-3 also has a two-axis sun sensor and an Earth sensor, as well as a deorbit device that includes an inflatable balloon that doubles as a tracking aid.

During the first phase of its mission, AeroCube-3 remained attached to the upper stage of the Minotaur launch vehicle by means of a 200-foot long tether, snapping photos of the upper stage with a wide-angle Video Graphics Array (VGA) camera to simulate an orbital inspection mission. In the second phase, AeroCube-3 cut its tether to become a free-flying spacecraft. At that point, magnets mounted on the satellite helped align it with Earth's magnetic field, enabling various attitude control experiments to be performed.

Aerospace Serves Panel Reviewing Human Spaceflight

Aerospace President and CEO Wanda Austin served as one of 10 panel members charged with reviewing NASA's Constellation human spaceflight program. The Human Space Flight Review Committee conducted an independent review of U.S. human spaceflight plans and programs, including available alternatives. The goal was to identify and characterize a range of options for continuing U.S. human space activities beyond the retirement of the space shuttle.

The committee assessed ways of expediting U.S. capability to transport equipment and personnel to the International Space Station, examined ways to support missions to the moon and other destinations beyond low Earth orbit, and considered ways of stimulating commercial spaceflight. It also made recommendations on how these goals can best be achieved within NASA's projected budget.

The committee, whose charter was signed June 1, summarized its findings in a final report presented Aug. 31. Former Lockheed Martin CEO Norman Augustine chaired the committee. Sally Ride, a member of the Aerospace board of trustees and a former astronaut, also served on the panel. "I am pleased to have had the opportunity to assist in planning the future U.S. human spaceflight program at this critical juncture," Austin said. Aerospace provided much of the analysis to the committee.

Astronauts Repair Hubble Space Telescope

The Atlantis space shuttle with seven astronauts aboard launched into space on a mission to repair the 19-year-old Hubble Space Telescope on May 11, 2009. The STS-125 mission was destined for a 14-day trip in which astronauts replaced or fixed everything from cameras to gyros to insulation on the ailing telescope.

Astronauts conducted five spacewalks, totaling nearly 37 hours. They installed a science instrument command and data handling unit, replaced the wide-field camera 2, installed six new gyros, and replaced three of the telescope's six nickel-hydrogen batteries. They also installed a "soft capture" mechanism designed to help with the future disposal of Hubble by a crewed or robotic mission.


Courtesy of NASA

STS-125 astronauts navigate the exterior of the Hubble Space Telescope on the end of the remote manipulator system arm, controlled from inside Atlantis' crew cabin.

Astronauts also installed a cosmic origins spectrograph, which will allow scientists to better study the universe and how planets formed and evolved. This new tool is designed to examine dark matter, which may provide insights into how the universe began.

Hubble's Advanced Camera Survey was also revitalized when outfitted with four new circuit boards and a new power supply. The camera is credited with sending back some of Hubble's most stunning imagery. The Space Telescope Imaging Spectrograph was also repaired; it was installed during a 1997 servicing mission but stopped working in August 2004 because of a power supply failure.

Lastly, the astronauts installed a new thermal material. It will protect Hubble's external blankets, preventing further degradation of the insulation, and will help maintain normal operating temperature of electronic equipment. With all of the new additions and repairs, Hubble is expected to last through 2014, when the James Webb Telescope is scheduled to take its place.

During the initial ascent phase of this mission, a piece of foam was liberated and struck some tile forward of the starboard wing of the Atlantis orbiter. Aerospace had previously developed an analytical tool for NASA that evaluates foam debris risk. This tool was built to predict foam debris risk as part of the return-to-flight effort following the failure of the Columbia orbiter caused by thermal protection system damage from a foam debris strike. Randy Williams, senior project leader, Space Launch Projects, said, "Aerospace determined the velocity and angle of impact for the STS-125 debris strike, which allowed the debris assessment team to conclude the tile damage had minimal depth and precluded the need for a more detailed inspection that would likely have reduced the timeframe for the astronauts to conduct their primary mission objectives." The astronauts returned to Earth, landing at Edwards Air Force Base in California on May 24, 2009.

A Fulfilling Career in Aerospace Research

Mark Hopkins' expertise in radiation hardness and space system survivability was a springboard to a broader career in technology and the innovative space efforts now taking flight in Albuquerque.

Nancy Profera

When Mark Hopkins decided he'd had enough of big-city living in Los Angeles, he pretty much created a job for himself and pitched it to management so he could move to the Aerospace office in Albuquerque, New Mexico. Now he's been there more than 15 years and is loving it. "We have many people here from both the East and West Coasts who prefer a more casual lifestyle," he said in a recent interview.

Hopkins is a long-time employee of The Aerospace Corporation, more than 20 years at this point. But he worked in and out of the aerospace for-profit sector for much of his early career, honing skills he later transferred to Aerospace. Hopkins earned a bachelor's degree in physics from Pomona College and a master's in electrical engineering from the University of Southern California. His father and a high school teacher both encouraged him to pursue an education and career in a technical discipline, he suspects, in his father's case, because there would be job security. Today, Hopkins' expertise lies in radiation hardening of microelectronics, space system survivability, space technology, and small satellite systems.

As principal director of the Space Innovation Directorate in Albuquerque, Hopkins is heading up national security space efforts that directly affect the military in its day-to-day efforts and address its urgent warfighter needs. The directorate supports three primary customers: the Space Development and Test Wing (SDTW), part of the Air Force Space and Missile Systems Center; the Space Vehicles and Directed Energy Directorates of the Air Force Research Laboratory (AFRL); and now the DOD Operationally Responsive Space (ORS) Office, formed in May 2007. Hopkins also is a key interface for collaborative efforts between Aerospace and Sandia National Laboratories.

"One of the best things about working in Albuquerque is we are building, launching, and operating small satellites, so we get to see all the aspects of space programs—from cradle to grave," said Hopkins. The directorate is involved with figuring out what R&D payloads to fly, how to acquire and build satellite buses, integrating payloads onto those buses, building the ground systems they will operate on, launching satellites, and operating them, since SDTW has its own satellite operations center. A year ago, Hopkins even made it to the Kwajalein Atoll in the Western Pacific, where he participated in a satellite launch and lived for two weeks at the Army installation on the island. "It was hot, a lot of work and long days, but a once-in-a-lifetime experience I'll never forget," he said.

Hopkins was most interested in research and development work when he began his career as an engineer in the late 1970s. His first job was at Litton, Guidance and Control, followed by work at the Northrop Corporation. At Northrop, his work included investigating single event phenomena in GaAs (gallium arsenide), total dose effects on HgCdTe (mercury cadmium telluride) array structures, and characterizing radiation effects on photovoltaic devices. He also began to coauthor several papers on these subjects with his colleagues. The Northrop position involved interaction with people at Aerospace, and he remembers discussing projects with Mike Daugherty, who retired as executive vice president, and Bruce Janousek, a principal engineer/scientist in the Physical Sciences Laboratory. Hopkins then came to work at Aerospace briefly, but was drawn away to Science Applications International Corporation by the "lure of money." After a year there, however, he got tired of constantly working the weekends required by the job. He moved on to a job at TRW, and two years later returned to Aerospace. He landed in the Engineering and Technology Group, and has been at the corporation ever since.

"One of the best things about working in Albuquerque is we are building, launching, and operating small satellites, so we get to see all the aspects of space programs—from cradle to grave."

All of these positions were building blocks that supported Hopkins' work in radiation effects. "The Reagan years were very good years. There were lots of job opportunities," he said. Although his career began during the Cold War, Hopkins said many of the technologies developed during those days remain applicable to today's space systems. "For example, there was a lot of investment in making electronics radiation hardened. These devices are used in building space systems today because, at a minimum, we still have to deal with the natural space radiation environment. Having that technology available makes our jobs easier by making sure critical subsystems will perform in an adverse environment," he said.

The ORS work Hopkins' group supports is a fairly new effort for the DOD. The mission is to develop the enablers associated with a responsive space architecture. The goal is different from the "big space" arena, where it may take five to ten years to develop a space system. The work instead is focused on "small space." "We're looking at developing enablers across the spectrum from launch vehicles, launch ranges, space vehicles, and payloads, to make the space deployment process go faster and be more responsive," he said. The other principal activity of ORS is responding to and making recommendations for urgent needs that come down from the warfighter. "The ORS effort is considered an adjunct to the type of large space and high-performance system work typically done in El Segundo. Obviously, you're not going to have the same type of performance with a small satellite. So you're trading performance for agility and speed in terms of acquisition, and the focus is on tactical support to the warfighter in theater," he said.

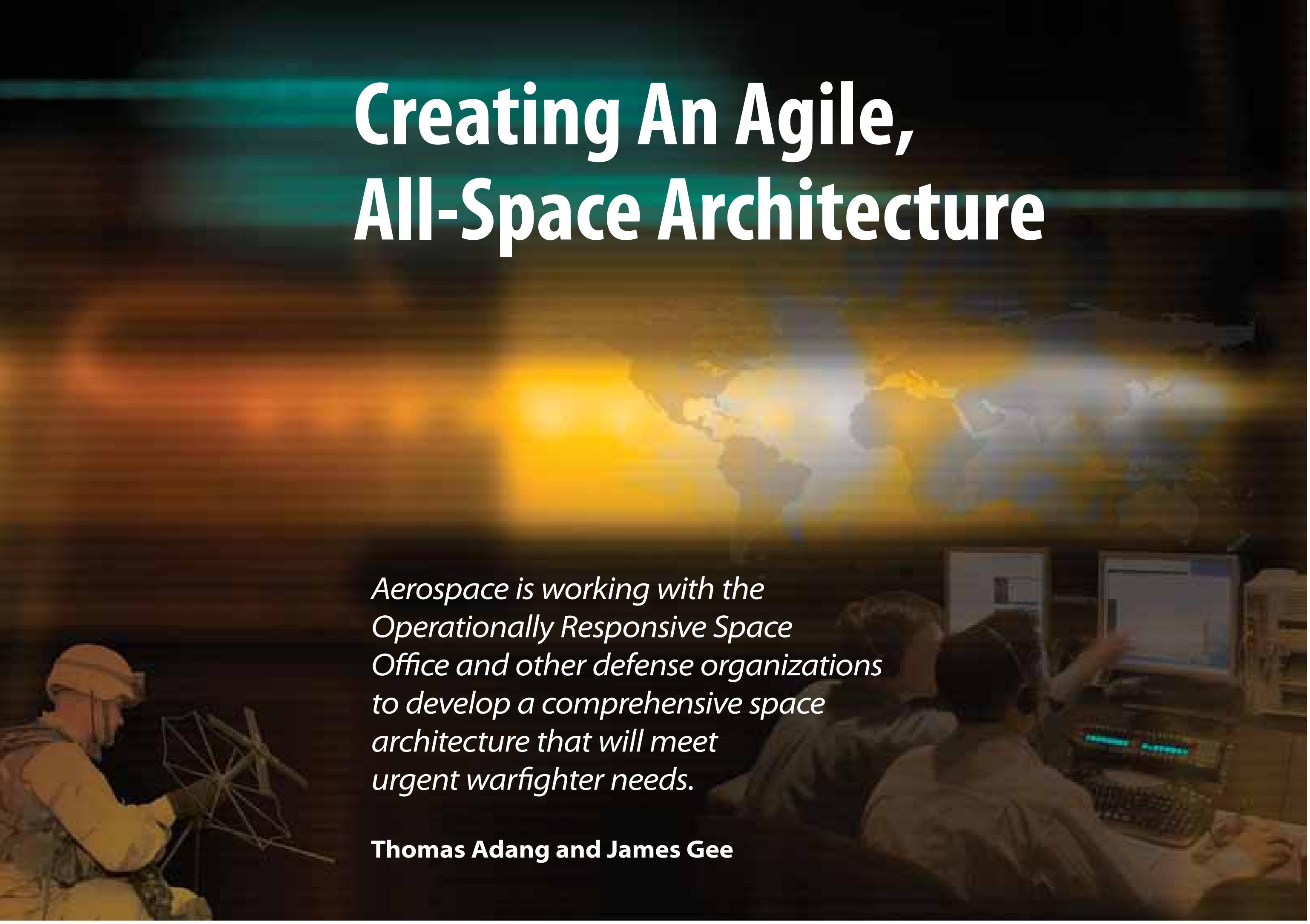
Hopkins explained the AFRL and SDTW efforts headed up in Albuquerque.

"AFRL develops space technology, and Aerospace works as its systems engineer on the technology demonstrations flown in space. A good portion of SDTW work is for the Space Test Program, flying research and development payloads for various DOD entities—Air Force, Army, and Navy. All three organizations [AFRL, SDTW, and ORS] are similar in that they're all very forward looking," he said. But occasionally, the needs of these three primary customers conflict, and Hopkins then counsels his staff: "Keep the discussion technical. Keep the emotion out of it. And try and work toward a solution that makes the best technical sense," he said.

As for his thoughts on management, Hopkins said, "A great deal of it is common sense and the ability to effectively communicate. The hard part is the people part, not the technical work." Hopkins explained the importance of communicating with employees and management. "You've got to understand their [employees'] needs, as well as your manager's needs, and trying to address those needs is extremely important," he said. "A key aspect is also leadership, which is different than management. You can be a good manager by following your STE [staff technical effort], capital, and overhead budgets, but that doesn't make you a good leader. To be a leader you have to understand the vision of your particular organization. You have to figure out what needs to be done and have the courage to execute those actions to make that vision a reality," he said.

Hopkins has been active in professional organizations throughout his career, including being the general conference chair for both the Nuclear and Space Radiation Effects Conference, and Hardened Electronics and Radiation Technology Conference. "I got involved to stay abreast of technical advancements in my field. Engaging with colleagues who have common technical interests in a small technical community, helping to put together the conferences and organizing them—it's just fun, that's the bottom line," he said. Hopkins has also taught "Key Enabling Technologies" at The Aerospace Institute. "Interacting with peers and sharing information is important," he said. He also wanted to broaden his perspective by looking across the space technology enterprise, and said, "What better learning experience could I have than putting together a course?" Hopkins teaches the introduction to the course, and then draws in different technical experts from across the company. "It's pretty unusual in that we have 10 or 12 instructors for the class," he said.

What has kept Hopkins working at Aerospace for 20 plus years now is the culture of the corporation and the work. "I've dabbled in a lot of different companies, and within the defense and aerospace industry, I don't think I ever found a place that treated their people better than Aerospace," Hopkins said, adding, "Aerospace is uniquely positioned to provide insight into and influence on some of the very important decisions our country is facing. How could you not be engaged in that kind of work? It's exciting."



Creating An Agile, All-Space Architecture

Aerospace is working with the Operationally Responsive Space Office and other defense organizations to develop a comprehensive space architecture that will meet urgent warfighter needs.

Thomas Adang and James Gee

For the past 40 years, the U.S. space architecture has been focused on what is now referred to as "big space." Most space systems provide exquisite capability, but it takes 5–8 years to build and deploy each. The "small space" systems that were developed and deployed more quickly were typically experimental or research satellites, providing little to no operational capability. Today, however, the increasingly complex role of space systems in all aspects of peacekeeping and warfighting has created highly varied needs for timeliness, persistence, data volume, and command and control—and with combatant commanders requesting more regionally focused space systems, small space is seen as an important part of a broader space picture.

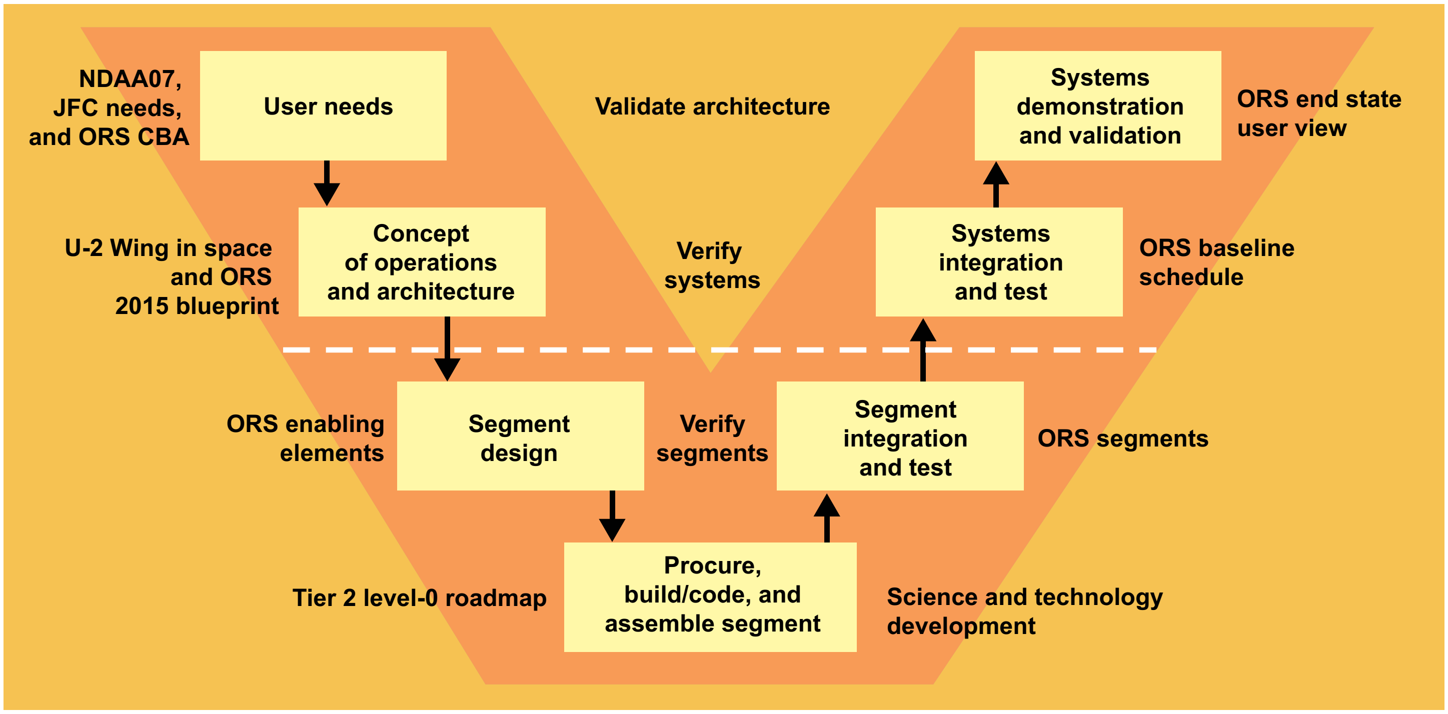
Defense planners have been increasingly vocal about the state of U.S. space architecture, aware of the need for change. They are not suggesting that the existing space architecture should be replaced; rather, they argue for an evolutionary move toward a balanced architecture that includes big and small space systems. Medium and large systems would provide the foundational capability, while small and less complex systems would provide additional capability in high-demand areas and niche capability for special operations and irregular needs. In short, the vision is for an agile "all space" architecture that can accommodate rapid changes and deliver a full spectrum of capabilities to the end user.

The Aerospace Corporation has supported big space for its entire existence, and has contributed to many of the trailblazing achievements in the small space arena. Drawing on this experience and expertise, Aerospace is now providing technical leadership to the development of an agile all-space architecture, working with all of the DOD entities focused on this goal.

Building the Architecture

The pursuit of more agility in U.S. space architecture is not new. In 2003, Air Force Space Command conducted an analysis of alternatives to determine the cost-effectiveness of operationally responsive launch and payload systems. The goal was to provide transformational capabilities synchronized to warfighter needs. The initial architecture was focused on incremental, spiral acquisition of reusable first-stage boosters, expendable upper stages, and responsive payloads. In 2005, the DOD Office of Force Transformation defined operationally responsive space (ORS) as a new business model, whereby space capabilities are designed for the operational commanders who drive the demand, which in turn defines the cost, risk, and mission-criticality. This model would require cheaper, smaller satellites with single-mission payloads and far shorter life spans. It was not designed to replace the larger space program, but to complement it. The smaller, less expensive satellites would serve as a testbed for larger space programs by providing a clear channel for science and technology investments. They would also provide a future ability to reconstitute larger space capabilities.

This effort led to the establishment of the tactical satellite (TacSat) program, with TacSats developed by the Air Force Research Laboratory and Naval Research Laboratory. TacSats were envi-



An architectural approach to building the operationally responsive space capability, which is based on the classic systems engineering "V." The vision is for a "U-2 Wing" in space with realization of the ORS 2015 blueprint. Verifying the segments and systems will occur prior to validation of the architecture.

sioned as stepping-stones to a more agile architecture, providing the scientific and national security space communities with an opportunity to demonstrate new technologies and new concepts of operation in space. Also in 2005, the Air Force led a joint effort known as Joint Warfighting Space that would provide space forces under control of the joint force commanders with responsive launch and space capabilities. These would be usable within hours or days instead of days or weeks and would be integrated with global national security space efforts and other theater systems.

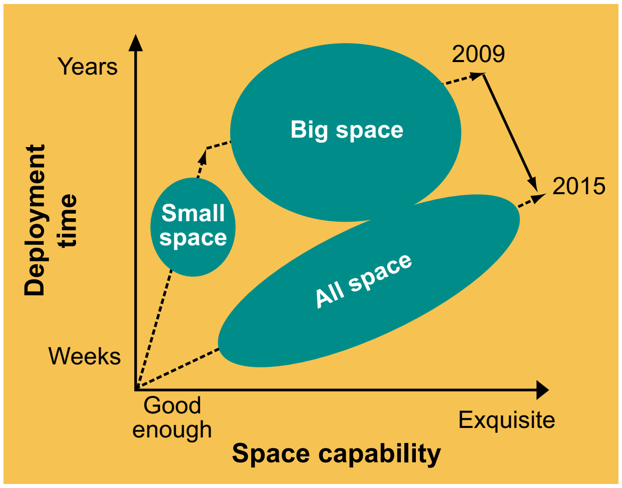
In 2005, U.S. space transportation policy stressed the goal of a more agile space architecture, one that focused on more than just rapid access to space. The policy clearly spelled out enabling functions for demonstrating operationally responsive access to space by 2010. Those functions (requirements and concepts of operation for launch, infrastructure, spacecraft, and ground operations) are critical building blocks to an agile all-space architecture. This policy served as a call to action for small space activities, and prompted Congress to direct DOD to establish an ORS Office.

The ORS Office was established at Kirtland Air Force Base, New Mexico, in May 2007. Approximately 60 personnel are assigned to the office, divided equally between government and contractor staff along with Air Force, Army, and Navy personnel. The office is also staffed by members of the National Security Agency, National Reconnaissance Office, the National Geospatial Intelligence Agency, and NASA. Aerospace personnel are also assigned to the office.

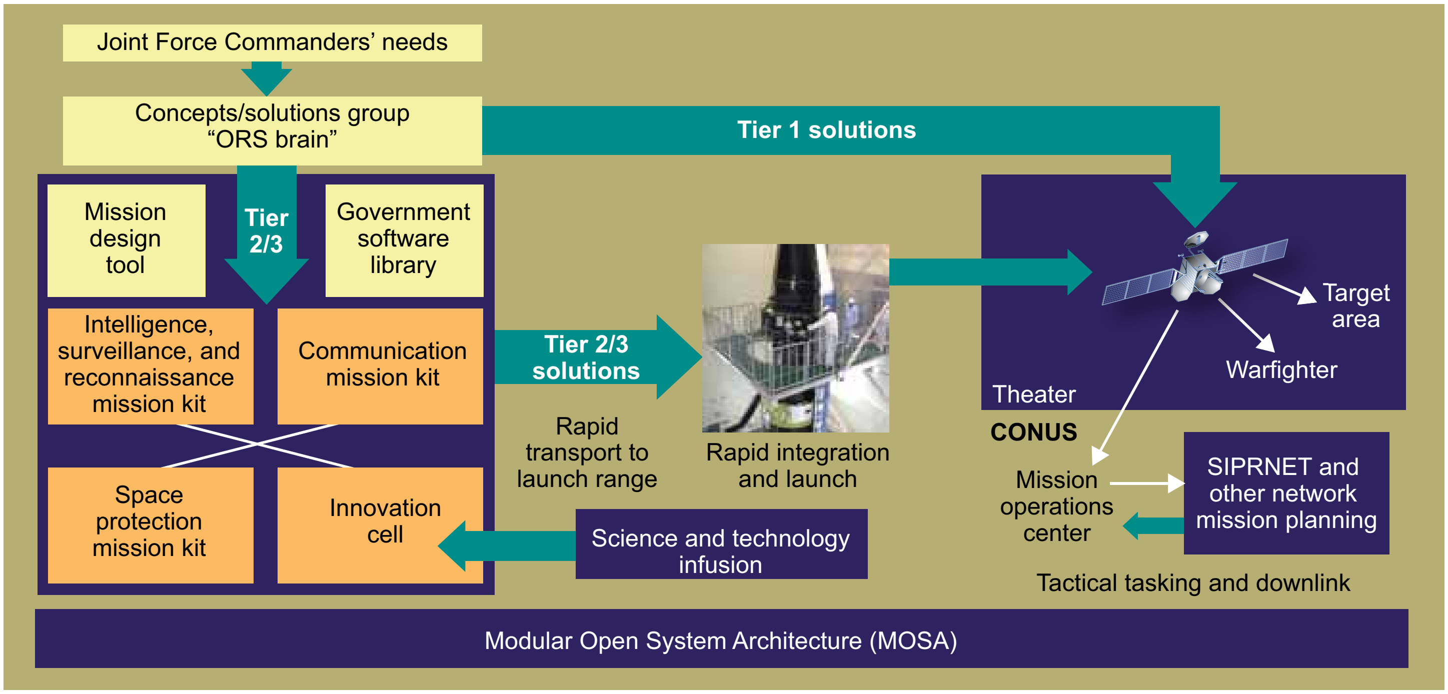
In the charter of the ORS Office, the DOD defined the ORS mission as "assured space power focused on timely satisfaction of joint force commanders' needs," and directed that the ORS implementation plan be developed and coordinated with the DOD and intelligence community. The ORS Office, according to the DOD, should be able to respond to joint force commanders' needs and develop end-to-end enablers for small satellites to provide timely space solutions.

In May 2007, U.S. Strategic Command further defined the focus and initial concept of operations for the ORS Office, which included rapid development of highly responsive space solutions (e.g., small satellite/launch vehicle combinations, and processing to convert data into actionable knowledge) and supporting concepts, tactics, techniques, and procedures. This established a tiered process by which the ORS Office and the national security space community would deliver space capability to the warfighter. The goal is to implement this tiered process by 2015 through a phased development approach comprising distinct "crawl," "walk," and "run" phases.

In 2007, Congress provided specific missions for the newly formed ORS Office. These included contributing to the development of low-cost, rapid-reaction payloads, buses, spacelift, and launch control capabilities to fulfill joint military operational requirements for on-demand space support and reconstitution of critical space capability lost to natural or hostile actions. The ORS Office would also coordinate



A notional concept of an all-space architecture with "good enough" to "exquisite" capabilities and a timeframe for deployment identified.



The ORS 2015 blueprint encompasses activities related to the bus and payload; launch and range; command and control; and tasking, planning, exploitation, and dissemination. The blueprint is driven by the needs of joint force commanders and the warfighter, and is based on a modular and open system architecture.

and execute ORS efforts across the DOD with respect to planning, acquisition, and operations.

Congress also directed the ORS Office to demonstrate, acquire, and deploy an ORS capability in support of military users and operations that consisted of responsive satellite payloads and buses built to common technical standards; low-cost space launch vehicles and supporting range operations that facilitate the timely launch and on-orbit operations of satellites; responsive command and control capabilities; and concepts of operations, tactics, techniques, and procedures that permit the use of responsive space assets for combat and military operations other than war, such as disaster recovery and humanitarian aid.

Congress provided the ORS Office with cost goals of $20 million for launch services and $40 million for procurement of an integrated satellite. These congressional directives and goals provided the initial architectural guidelines used by the ORS Office to establish its vision and approach.

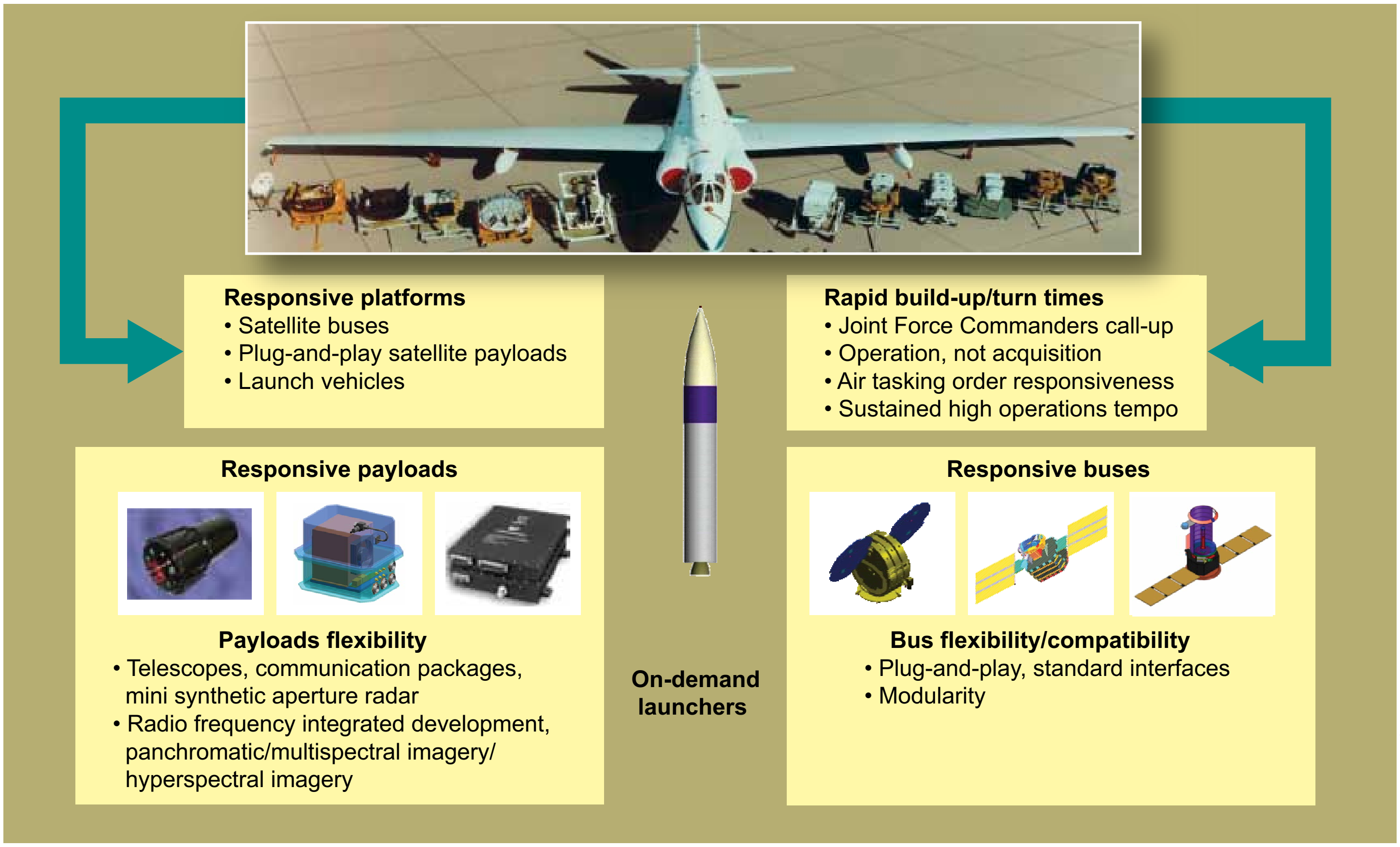
Filling the Small Space Void

The ORS Office is taking a standard systems engineering approach to achieving the 2015 end-state vision or "blueprint." Steps have been taken to define user needs, develop a concept of operations and end-state architecture, assess and plan for development of necessary segments of that architecture, and begin to procure and build individual segments. User-specific missions are the glue that allows segment integration and testing, systems integration and testing, and systems demonstration and validation. The result is mission capabilities that meet the initially specified user needs.

The ORS Office selected the Space and Missile Systems Center's Space Development and Test Wing at Kirtland Air Force Base, New Mexico, to manage the development and fielding of the first ORS mission known as ORS-1, designed to meet a critical U.S. Central Command need for intelligence, surveillance, and reconnaissance (ISR). ORS-1 will modify an existing airborne payload and use existing tasking, processing, exploitation, and distribution systems. It will be put into orbit on a Minotaur launch vehicle. The ORS-1 mission will fill a warfighter gap and develop and exercise many of the key ORS enablers necessary for future ORS missions, such as enhanced small satellite performance, reduced launch schedule, open command and control, and timely dissemination of information to the warfighter using existing tactical networks. The ORS Office is also assessing other joint force commander needs in the areas of ultrahigh frequency (UHF) satellite communications, space situational awareness, and ISR.

The ORS 2015 blueprint flows from warfighter needs and derives from the initial ORS concepts of operation defined by U.S. Strategic Command for Tier 1, 2, and 3 timelines (capabilities within hours, weeks, and months). There are several key components to the architecture: a "design cell" that develops concepts/solutions in response to a joint force commander need; a series of mission kits that provide payload capability; standard platforms on which the mission kits are integrated; a rapid assembly, integration, and test capability; a rapid integration and launch function; and a ground enterprise architecture that ensures actionable information is provided to warfighters. The initial design cell has been established and exercised in response to the joint force commander needs provided by U.S. Strategic Command. Those needs also indicated the priority mission kits (communications, space situational awareness, and ISR) that will need to be developed. This development is underway, and the ISR payload on ORS-1 could serve as the operational prototype for a future mission.

This model for responsive space is a space-based version of the U-2 Wing. The goal is to bring the timeliness of air tasking orders to space operations. Like the U-2 Wing, the ORS Office is working to establish standard platforms (i.e., buses), mission kits (i.e., payloads), and interfaces to enable rapid integration and call-up. The infrastructure will be based on a modular open systems architecture and open standards for hardware and software. The plan is to control long-lead items through the use of a Rapid Response Space Works facility.



Airplane image courtesy of U.S. Air Force

The concept of operations for responsive space. Necessary enablers are identified, including a range of responsive platforms, payloads, and buses. Rapid build-up and turnaround times, on-demand launchers, and payload flexibility all play a vital part in creating this new paradigm for space.

Key functions of this facility will be rapid assembly, integration and testing, and integrated logistics support. The ORS Office and the Space Development and Test Wing are working to develop the Rapid Response Space Works prototype.

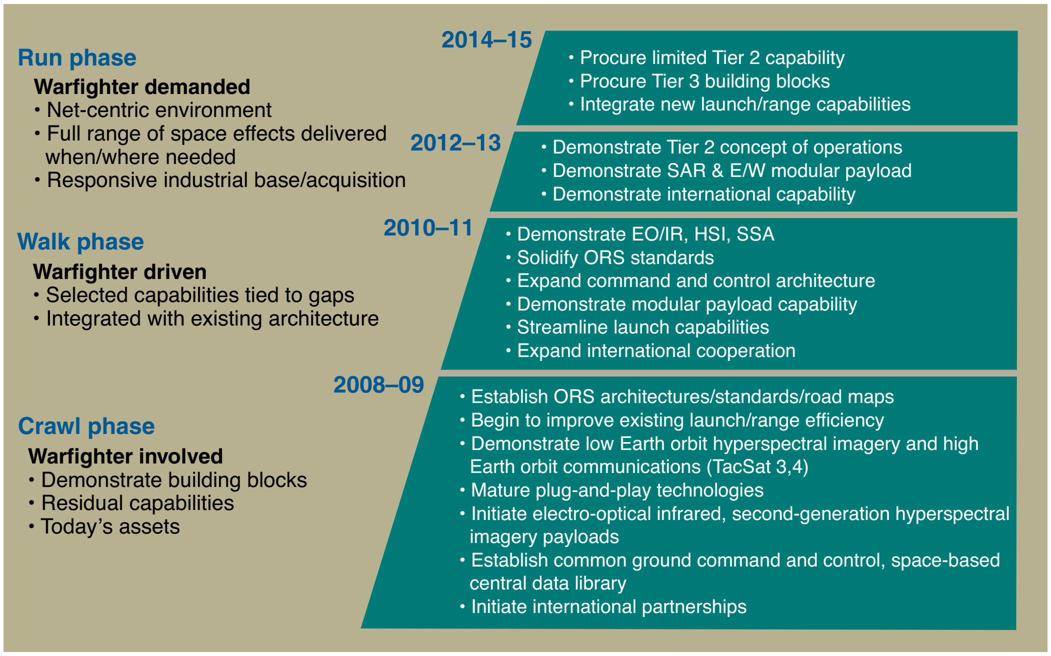
The diverse set of investments required to achieve the 2015 blueprint are known as ORS enablers or pillars of responsive space. They generally fall into the categories of launch and range; buses; payloads; command and control; tasking, processing, exploitation, and distribution; concepts of operations; and authorities. These enablers can also be viewed as architecture segments; each is a dependent entity that must be built and integrated to ensure the needed capability is met. ORS-class satellites are currently in the 500 kilogram range, and this class of satellite drives pillar development strategies.

For example, the ORS Office primarily relies on the Minotaur I and IV launch vehicles, though it is also investigating the use of other launch vehicles, such as the SpaceX Falcon series, that would move it closer to congressional cost goals. Range enablers are more of a challenge. Several U.S. launch ranges exist (e.g., Cape Canaveral, Vandenberg, Wallops, Kodiak, and Kwajalein), but not all of these can accommodate small launch vehicles, and none is currently configured to meet the Tier 2 launch capability. Achieving Tier 2 and 3 goals will require significant investment in modular and reconfigurable satellite bus and payload architectures, technologies, and concepts of operation.

The strategy for satellite command and control and tasking, processing, exploitation, and dissemination is to first leverage existing airborne infrastructure. This approach addresses the goal of assured space power focused on timely satisfaction of commander needs, but creates another major challenge in developing a responsive space concept of operations that is integrated with the broader national security space operational architecture. The ORS Office must work throughout DOD and with other government agencies to ensure that authorities are operationally responsive. This involves establishing international relationships and developing processes for rapid contracting and acquisition, information assurance, and frequency allocation and registration. The world's leaders in small satellite operations are in the United Kingdom, Germany, and Israel, and the United States can benefit from teaming with these partners. In addition to developing small satellite bus and payload technology and bringing space systems into coalition warfare, U.S. international partners are providing "nonmaterial" enablers. For example, because of the time it can take for approvals, frequency allocation and registration approval can be a multiyear process, and must be treated like long-lead items for payloads and buses.

Procuring, building, coding, and assembling segments are typically space industry tasks, and the space industry must be involved for the mission of an all-space architecture to be a success. Soon after its establishment, the ORS Office began to aggressively engage the space industry, recognizing that substantial changes in the industrial base were necessary to successfully build ORS enablers. For example, in February 2008, the ORS Office held its first ORS Industry Day, and in March 2008, released three Broad Agency Announcements for building ORS enabling capabilities in launch, range, modeling, architecture, and modular spacecraft payload and bus capabilities. Subsequently, the ORS Office issued more than 20 contracts worth more than $18 million.

These contracts, along with the startup of the Rapid Response Space Works and the development of ORS-1, are just the beginning of enabler development. The next step is to ensure the development of a cross-enabler program and road map that clearly points to a phased delivery of a U-2 Wing in space from now through 2015. This capability will provide an inventory of modular buses and payloads, where standard interfaces enable "plug-and-play" assembly in response to joint force commander requests. Coupled with a responsive infrastructure that provides launch, operations, command and control, and dissemination, this capability will serve to better integrate space with air and ground expeditionary forces and sustain high operational tempos.



A phased approach to developing enablers for responsive space. The objectives include reaching milestones for the crawl, walk, and run phases of achieving the 2015 blueprint for space. All phases are designed to respond to warfighter needs.

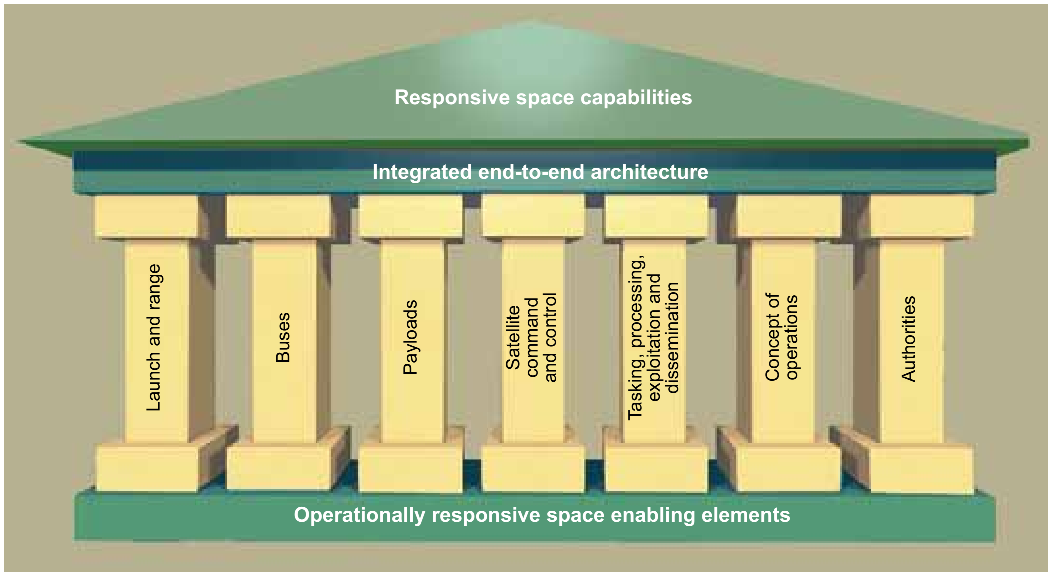
Aerospace's Role

Aerospace has been supporting all facets of the development of an agile all-space architecture. Aerospace provided fundamental technical analysis leading to the ORS construct and provided critical support to the effective stand-up of the ORS Office. Aerospace analysis of small satellite concepts, architectures, and utility supported the initial Joint Warfighting Space activities in 2005, the National Security Space Office Responsive Space Operations Architecture Study in 2006, and the Air Force Research Laboratory's trade space evaluation of the TacSat series. In 2007, Aerospace helped compose the "Plan for Operationally Responsive Space," which the DOD submitted to Congress. It established the Aerospace support plan for the ORS Office and proposed an operational satellite study to guide the initial ORS satellite investment strategy. Aerospace also established an ORS Community of Practice in June 2007, which was designed to identify, consolidate, and document cross-organizational knowledge and corporate positions on ORS. The community also guides corporate efforts for comprehensive and consistent exploration of ORS concepts and implementations. It has been an effective mechanism for coordinating Aerospace support—especially for the development of ORS-1 and the planning for ORS-2, potentially a small radar satellite.

Aerospace has led the ORS response process for joint force commander needs, ensuring critical support was provided to warfighters in the areas of UHF satellite communications and space situational awareness. Aerospace also functions as chief systems engineer and architect for the ORS Office, working with a collocated research consortium that helps the ORS Office solve difficult systems engineering problems.

Other Aerospace efforts include leading a warfighter requirements assessment, establishing an ORS government/industry consortium for defining and implementing modular open system standards critical to development of the ORS 2015 blueprint, and creating a ground system enterprise architecture necessary to deliver space-based actionable information directly to the warfighter.

A key role of Aerospace is to foresee the challenges of implementing the ORS vision. The ORS Office will face numerous decisions on alternative paths forward. For example, an understanding of launch-on-schedule versus launch-on-demand will help plan the operations of the Rapid Response Space Works. Aerospace is also



Responsive space capabilities that are integrated in an end-to-end architecture. These are the necessary building blocks for an agile, all-space architecture, and are based on a pillared approach supported by enabling elements.

conducting a study on the feasibility of on-demand launch and operation. This concept involves the ability to quickly provide a new space-based capability or augmentation with very little notice, and requires coordinated command and control, satellite, and ground systems. The objective of the study is to define methods for accomplishing on-demand launch and operation. Key questions include:

- How much time is allowed or required from "cold-start" to initial on-orbit services? How does this affect launch vehicles, space vehicles, and ground systems?
- What are the missions and orbits? This requires determining launch vehicle capabilities and the location of launch sites. A broad range of orbits for a mission may require the use of multiple launch sites and multiple payload options.
- What are the mission parameters? These include location of interest, resolution, field-of-view, coverage per day, etc. This must also satisfy coverage requirements, potentially requiring more than one satellite and may involve multiple launches or a larger launch vehicle to carry multiple satellites.
- How many launches are required, and for how long? This depends on requirements (10 launches per year, month, or day?) and determines launch vehicle and space vehicle fleet sizes, facilities architecture, and suitable ranges.

Although ORS missions can be deployed for space force enhancement, space control, and space force application, this study focuses on space force enhancement, including communications, ISR, environmental monitoring, missile warning and battle space characterization, and navigation and timing. This study also examines various concepts of operations for ground processing, including the use of fully integrated launch and space vehicles stacked on launchpads; space vehicles integrated with upper stages stored in ready condition; space vehicles integrated with fairings stored in ready condition; and space vehicle "standard" buses and multiple payloads stored at a site, all of which would be awaiting call-up determined by payload need, integration with bus, launch vehicle, and launch.

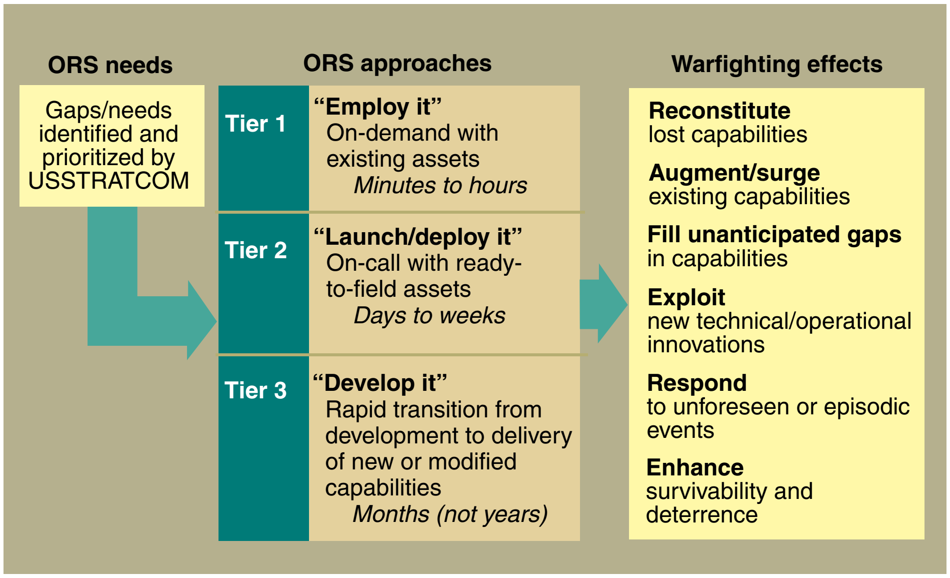
Summary

Senior national leaders have clearly stated the need for an agile all-space architecture. Today, the biggest capability shortfall is in the small space domain. Substantial efforts have been made to address this shortfall, including the establishment of an ORS Office to accelerate national security space actions to build the small space architecture and to instill agility into big space processes.

Aerospace has been a key participant in efforts to develop an agile architecture, having established a strong cross-disciplinary team to assist the national security space community in building that architecture. Consistent with its core competencies, Aerospace has helped develop the systems engineering and architecture approach to building agile all-space capabilities required by the warfighter and has been instrumental in assisting the ORS Office in its early successes.

A focus on agile all-space architecture and ORS is not likely to change. Congressional support for ORS capabilities remains strong. President Barack Obama said, "We should protect our assets in space by pursuing new technologies and capabilities that allow us to avoid attacks and recover from them quickly. The ORS program, which uses smaller, more nimble space assets to make U.S. systems more robust and less vulnerable, is a way to invest in this capability."

The challenges to building an agile all-space architecture are many; the risks (political, technical, and fiscal) in the ORS approach are significant. Some still question the military utility of small satellites, but there is growing evidence that small satellites are providing clear military utility. Large, multimission, high-performance satellites cannot be everywhere all the time. Meanwhile, small, sufficiently capable satellites are proving their capability can be a match to user needs. Building an agile all-space architecture will require staying the course through the "crawl, walk, run" development phases to ensure the 2015 end state is realized, with the warfighter clearly being the beneficiary. Aerospace support will be critical to achieving this vision.



A figure displaying tiered timelines for delivery of space capabilities. Gaps and needs in warfighter capabilities are identified and prioritized by U.S. Strategic Command before a tiered approach is decided upon.

Further Reading

Kendall K. Brown, "A Concept of Operations and Technology Implications for Operationally Responsive Space," *Air & Space Power Journal* (Summer, 2004).

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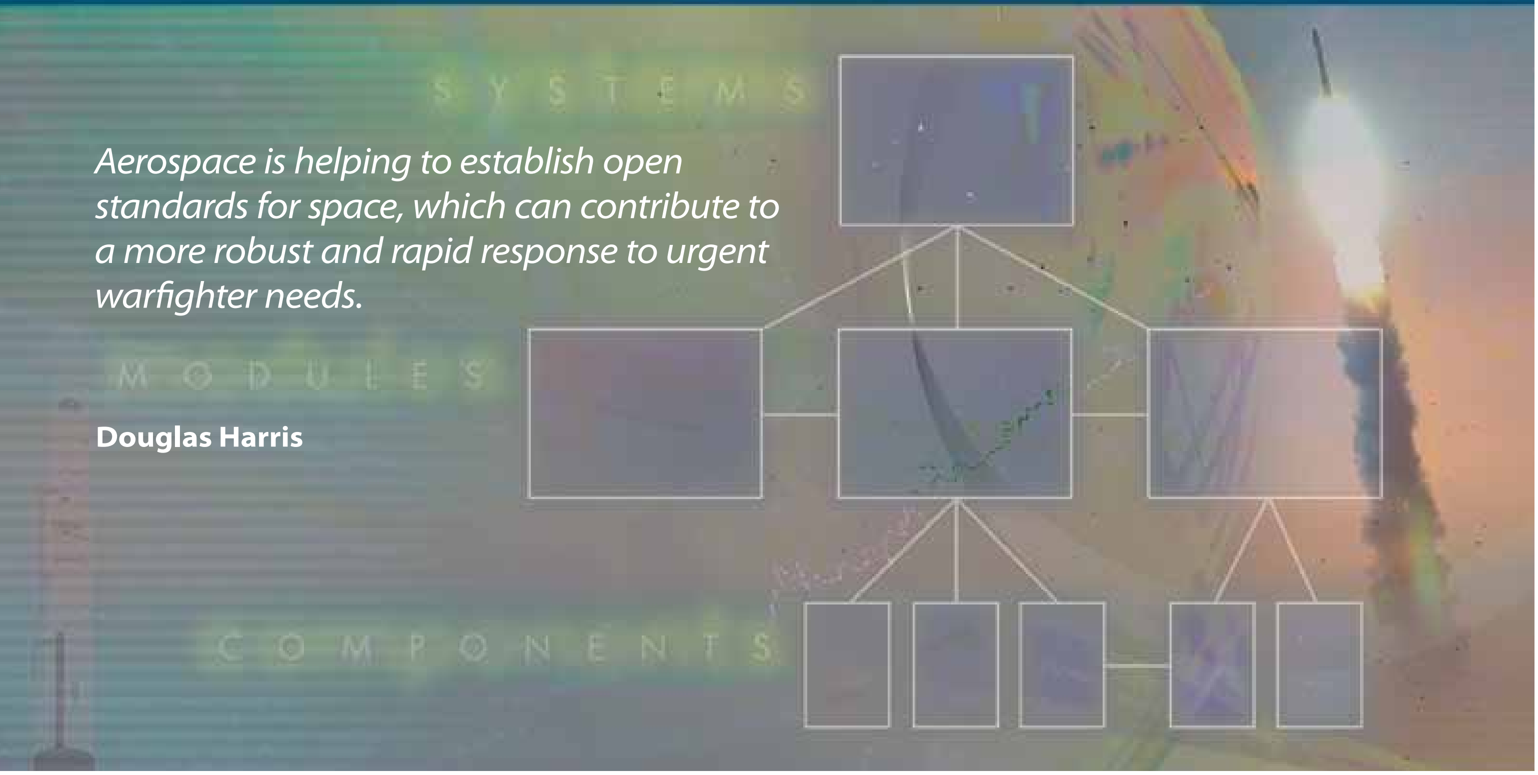
Open Architectures and Standards for Agile Space



Aerospace is helping to establish open standards for space, which can contribute to a more robust and rapid response to urgent warfighter needs.

Douglas Harris

Imagine having only a few months to transform a fully operational unmanned aerial vehicle from its passive reconnaissance mission to a lethal weapon system ready for immediate deployment to theater. The task of successfully completing all of the phases from requirements definition to full operations in such a short timeframe would seem daunting, if not impossible. But such was the case with the Predator vehicle, which was equipped with Hellfire missile capabilities for immediate deployment to Afghanistan in 2001. This is an example of how development teams—in just over 30 days—were able to rehost critical target-tracking software from the line-of-sight, antitank weapon system to the Predator's computing environment.

Much of the credit for this success goes to the Army's open Weapon System Common Operating Environment and its application programming interface. This operating environment isolates unique software functions from the equally unique underlying operating systems and hardware. It specifies common services for managing the 1553 serial data bus and handling digital video on the Predator system. As an open and standard interface, it eliminates the need for unique integration with each new application. In the case of the Hellfire missile, it not only facilitated rapid integration and fielding on the Predator, but it did so with as much as a 75 percent reduction in software development costs while allowing seamless integration into an existing theater of operation. That is the value of open architectures and standards: they foster rapid innovation at much reduced cost and risk.

A recent Defense Science Board report on open systems cites the major challenges of growing operational demands, shrinking budgets, and rapidly changing technology as reasons for pursuing more open and agile architectures. The report states that "DOD can neither equip, train, support, nor fight in this new world without major advances in plug-and-fight capabilities…we find no viable or practical alternative for delivering warfighter capabilities better, faster, and cheaper."

The typical lead time for new systems within DOD and national security agencies does not accommodate the dynamic operational needs of users, nor can it exploit the benefits of a rapidly advancing technology base. The importance of maintaining global superiority within growing operational demands and shrinking budgets requires a more agile process for responding with the most technologically up-to-date and cost-effective solutions.

Studies and experience demonstrate that open architectures, system modularity, and common industry-supported standards will enable rapid assembly, integration, and deployment of space systems at lower cost. They can also contribute to a more robust and responsive industry base necessary for achieving responsive space objectives.

One of the best examples of an industry collaborating to create an open architecture and standards is the World Wide Web Consortium, the international organization that develops standards governing the Web. Amazingly, as expansive and powerful as the World Wide Web is today, it is built upon a relatively small number of open standards and protocols. The result is an open and standardized domain that is easily exploited for the innovation of competitive products and services across a multitude of markets. Another example is the Open Handset Alliance, a group of 50 technology and mobile communications companies that collaborated to develop a common software platform for hosting mobile applications. The alliance credits increased openness with enabling people to innovate more rapidly and respond better to consumer demands. The use of common, consensus-based services has allowed member companies to focus their resources on other efforts, such as producing the next great application.

Adopting a collaborative approach toward open architectures and standards for space presents an opportunity for the military services, national agencies, and space industry to pursue innovations in technology and practice that not only yield a greater return on investment, but are more responsive to the warfighter.

Operationally Responsive Space

The Operationally Responsive Space (ORS) Office, located at Kirtland Air Force Base in Albuquerque, New Mexico, was established in May 2007 with the mission of developing the end state architectural blueprint and supporting technology roadmaps that will enable space system developers to field capabilities that can rapidly respond to joint force commander (JFC) needs. Aerospace is supporting the ORS Office in its charter of demonstrating operationally responsive access to space by 2010 with full mission capability by 2015. Full mission capability includes delivering a broad range of "good enough to win" space capabilities to any JFC worldwide—faster and cheaper than what it takes to field "exquisite" capabilities today. The ORS Office is charged with conducting operational prototype missions that not only address real-time JFC needs, but mature and validate the blueprint and enabling technologies that will constitute an operational architecture. Once demonstrated, the ORS Office will transition the validated architecture, enablers, and supporting concept of operations, tactics, techniques, and procedures to the military services and/or other national security and space agencies for full-scale acquisition, operations, and lifecycle support.

The ORS Office envisions a future capability for responsive space that models a U-2 Wing, whereby specific operational needs are addressed by mating the appropriate mission kit with a common platform.

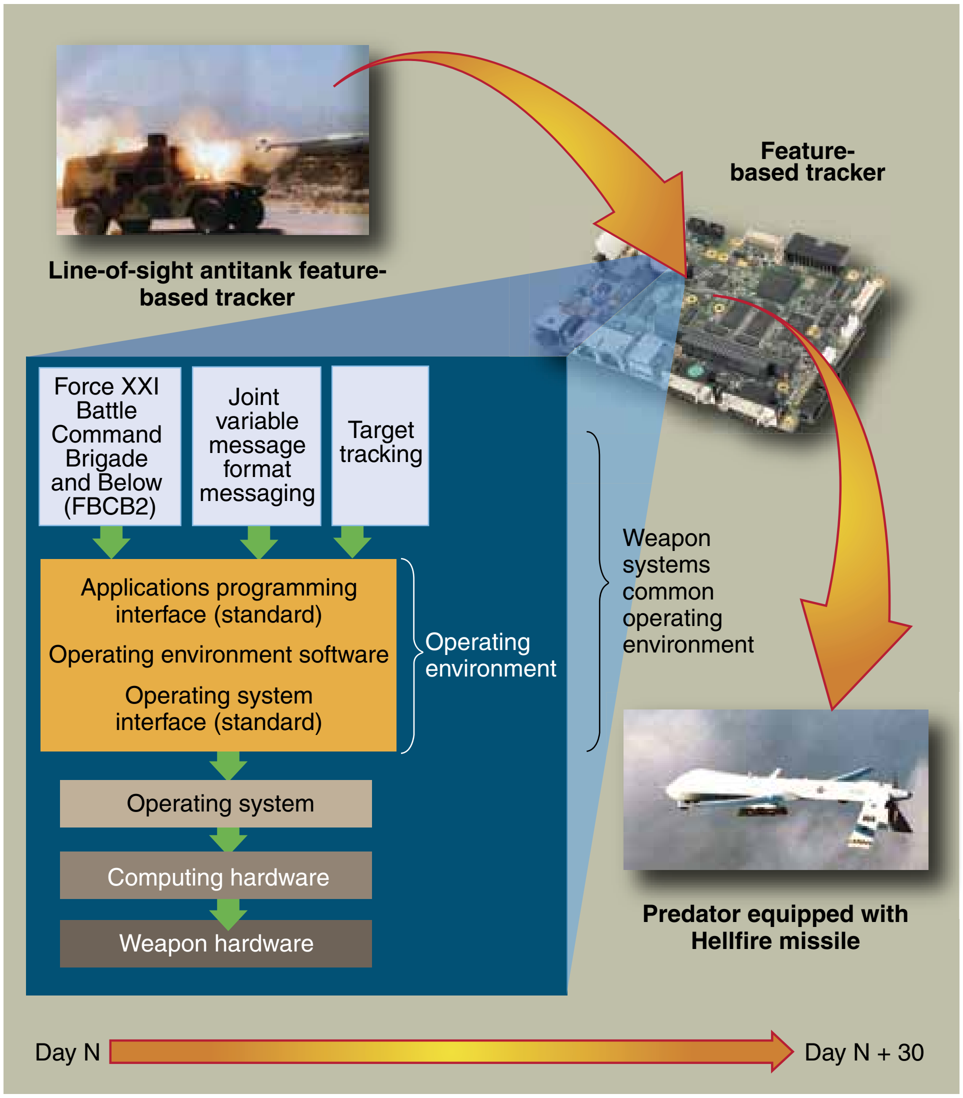


Image insets courtesy US Army and NASA

A Predator unmanned aerial vehicle was augmented with Hellfire missile capabilities in about 30 days for rapid deployment to Afghanistan. Critical target tracking software was easily rehosted from the line-of-sight antitank computing environment to the Predator's because it was built upon the Army's open weapon system.

Aerospace is supporting the ORS Office in defining this space-based version of a U-2 Wing that can respond to urgent tactical needs by mounting "payload mission kits" to a modular and reconfigurable multimission spacecraft bus for rapid launch and immediate operations.

Modular and Open Systems Approach (MOSA) for ORS

The ORS Office has adopted the Modular and Open Systems Approach (MOSA) in pursuing the open architecture and standards necessary to achieving its goals. MOSA represents the most promising approach to achieving the agile end-to-end space architecture that can rapidly and efficiently respond to JFC's urgent needs.

MOSA is an integrated business and technical strategy based on five primary principles for developing new systems or modernizing existing ones. These include establishing an environment conducive to open system implementation, employing modular design tenets, defining key interfaces where appropriate, applying widely supported consensus-based (open) standards that are published and maintained by a recognized industry standards organization, and using certified conforming products.

The ORS Office strategy for MOSA relies heavily upon an extended responsive space enterprise consisting of military services, national space agencies, early adopter development teams, and the overall space industry. Aerospace is assembling the tools for a networked community of practice to both inform and engage the responsive space enterprise in ORS Office business decision and systems engineering processes. This enterprise is a principle driver

Spacecraft payload class	Missions as defined by needs	Spacecraft bus class
Electro-optics payload	Electro-optical intelligence, surveillance, and reconnaissance	LEO – (moderately agile, stable)
	Space situational awareness	LEO – (moderately agile, stable); LEO/HEO – (highly agile)
	Nonimaging infrared–FAC	HEO – (moderately agile, stable, radiation hard)
Radio-frequency payload	Synthetic-aperture radar–CCD	LEO – (moderately agile, stable)
	Communication Blue Force tracking	HEO – (standard agility and stability, radiation hard)

Modular and open payload/bus architectures are key to rapid innovation and response across the operationally responsive space mission.

Grouping missions by bus and payload technology helps identify commonality. Maximizing commonality supports reuse of common core components into common core configurations, which minimizes the reconfiguration required in responding to a mission need. This, in turn, contributes to an agile space environment.

in defining the appropriate levels of modularity, identifying key interfaces, and recommending preferred open standards that support each "business case" for ORS. ORS will not succeed by creating an isolated market. The success of achieving responsive space depends on merging ORS needs with the wider commercial market, where both can realize the economies of scale and benefits of open space architecture.

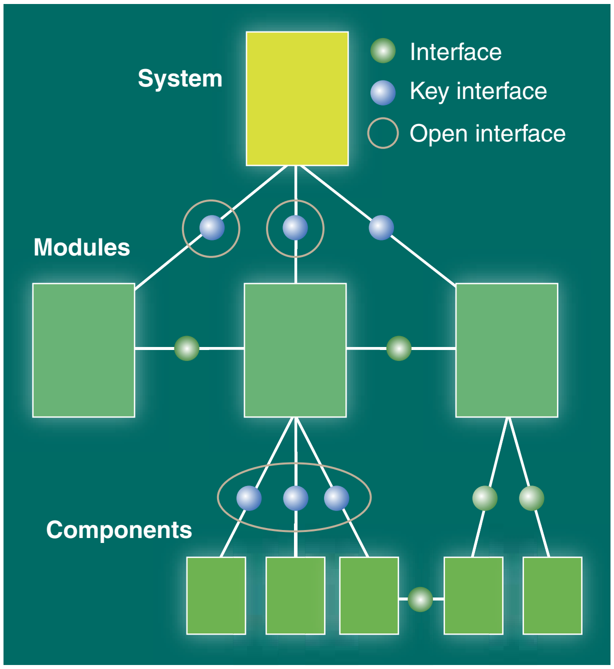
Defining modularity and identifying the key interfaces is a top-down process focused on maximizing the business, operations, or "industrial" benefits. The market business case, intellectual property, commonality of components across missions, industrial process efficiencies, logistics, component reuse, criticality of function, volatility of technology, and external interoperability are just some of the drivers that will help identify the key interfaces. For example, the ORS Office is currently looking into key interfaces that define the use of common optical telescopes or antenna reflectors with interchangeable back-end electronics for meeting multiple missions. Common components permit common processes that reduce the assembly, integration, and testing timeline, and also reduce personnel and equipment overheads, with increased process efficiencies over time.

The ORS Office strategy for MOSA also supports international engagement objectives that are focused on revitalizing the U.S. space industry and strengthening alliances. MOSA-developed architectures and standards have the potential to revitalize the U.S. space industry by fostering more effective international partnerships and leveraging existing relationships for the use of best available technologies. It enables crossover of systems or components to commercial and international export markets, permitting economies of scale that are typically seen only in commodity production markets. An analogy is the sale of U.S. F-16 and F-35 aircraft and associated components to allied nations. Systems produced for export at lower cost with basic capabilities can expand international markets, creating a broader and more robust inventory of systems and components for responding to allied operational needs.

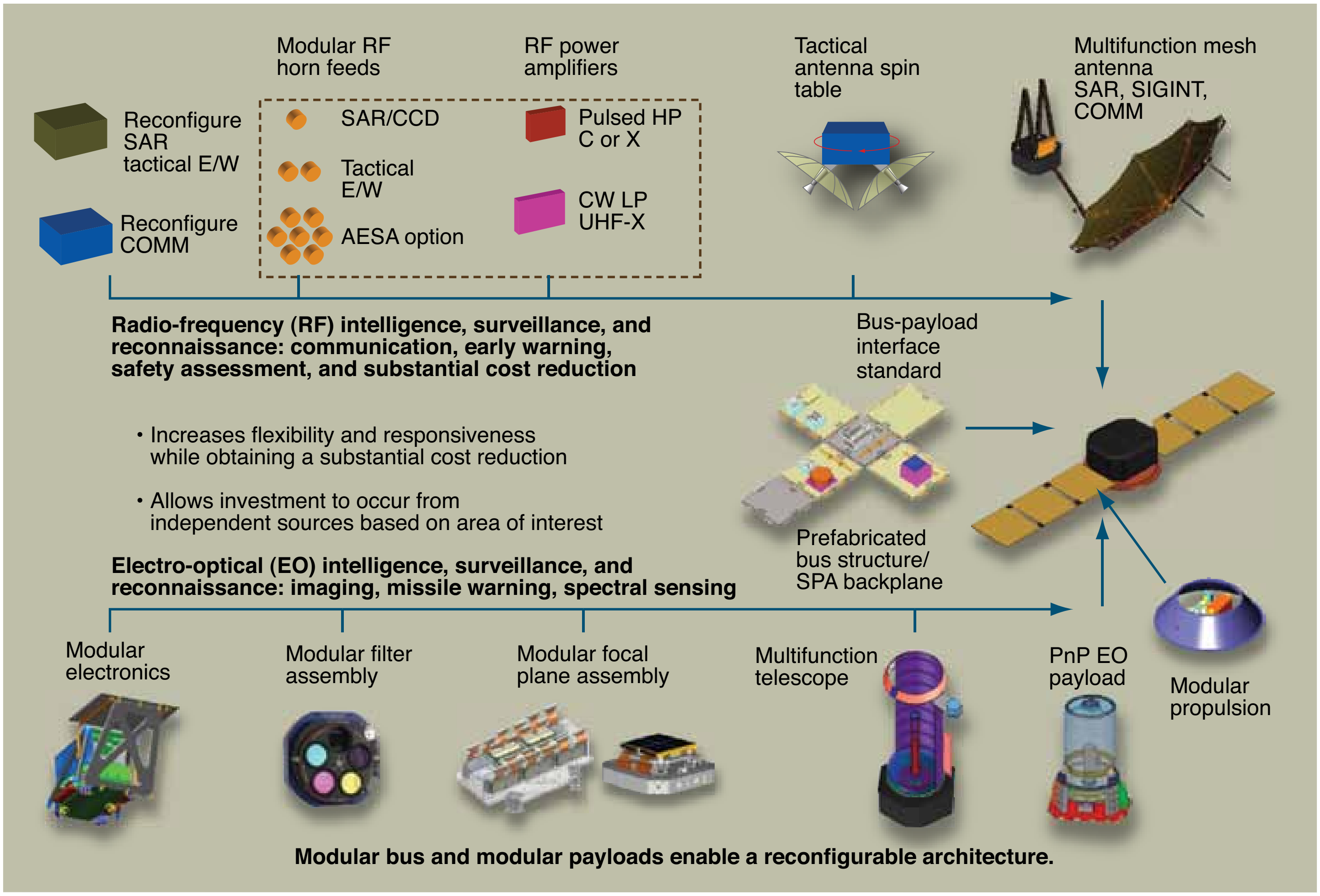
ORS MOSA and Standards Implementation

At the heart of the 2015 blueprint for ORS is the Rapid Response Space Works (RRSW), which will respond to JFC needs by rapidly assembling, integrating, and testing the appropriate mission spacecraft from within hours to days. Aerospace is supporting the ORS Office in developing a prototype RRSW called "Chile Works" at Kirtland Air Force Base. The application of MOSA guides the development of spacecraft architectures to an optimal level of modularity that enables the RRSW to rapidly respond to operational needs without maintaining a large, expensive inventory of hardware and personnel. Moreover, MOSA drives the open interfaces that permit fast and economical insertion of fresh technology and innovation. Finally, MOSA serves to integrate RRSW operations with the other components of the end-to-end mission architecture, such as space vehicle transport, launch and range, command and control, tasking, and data dissemination.

Aerospace is working with the ORS Office, the space industry, and other defense and national agencies in identifying open standards for potential key interfaces. The standards strategy of "adopt, adapt, and as a last resort develop" has led the ORS Office to leverage heavily upon existing standards work within the command and control, tasking, processing, exploitation, and dissemination (C2/TPED) and launch communities. A major area of standards work for the ORS Office is defining the spacecraft architecture and standards that enable responsive operations. The vision of building a space-based U-2 Wing calls for developing a common mission platform (a multimission bus)



The modular and open systems approach calls for systems engineering processes that employ modular design tenets and identify key interfaces where open standards should be applied. Defining "key interfaces" and "open standards" is a top-down process focused on maximizing the business, operations, or space industry benefits.



This diagram illustrates a flow of common components for multiple missions that consolidates processes based on physics (i.e., radio frequency, optical, and bus). Common processes reduce personnel and equipment overheads and enable increased efficiency for a more rapid response over time.

that can rapidly integrate and launch on the Minotaur 1, Minotaur 4, or Falcon 1E launch vehicles into either LEO or HEO orbits. A modular multimission bus architecture must be defined to support responsive operations through its ability to rapidly reconfigure (to the extent necessary) for the full range of ORS payload "mission kits" and orbits. A multimission bus that maximizes reuse of common core components in common configurations is a multiplier for RRSW operations as it maximizes the reuse of assembly, integration, and test equipment and procedures, thus reducing timelines, inventories, personnel, maintenance, and training.

The ORS Office has adopted two major bodies of work as input to its standards activities. The first is a body of standards developed by the Integrated Systems Engineering Team (ISET); commissioned by the Office of the Secretary of Defense, Office of Force Transformation in 2005 to produce an optimized set of performance requirements and standards for meeting potential ORS missions. The second is the Space Plug and Play Avionics (SPA) standards developed by the Air Force Research Laboratory. The ISET standards specified a generic one-bus-fits-all description in addressing the maximum number of ORS missions. Meeting the full range of ORS missions, however, requires adjusting the ISET standards to a modular and reconfigurable multimission bus. The SPA architecture and standards enable this additional level of modularity for responsive operations by addressing the full spectrum of ORS missions. As a result, the ORS Office is working to incorporate and demonstrate the SPA standards within the existing ISET definition to produce a validated ORS multimission bus architecture.

The SPA architecture with its Satellite Data Model manages the self-discovery of SPA-enabled hardware and software components, much like the way personal computers recognize and configure USB components and peripherals. Self-discovery provides a means to rapidly assemble or reconfigure satellite systems. Each SPA-enabled component is described by an XML-expressed data sheet, called the "extensible Transducer Electronic Data Sheet" (xTEDS). The TEDS standard was originally created by the IEEE 1451 standards group as a means of storing device descriptions within each individual device. The xTEDS uses both XML and TEDS standards to provide a structured way to describe the features, actions, and services (data, commands, interfaces, and requirements) of each SPA-enabled component. The SPA architecture employs an IP-based protocol to route messages point-to-point between SPA-compliant components using the widely accepted SpaceWire transport standard. It will also register components (both hardware and software) along with their capabilities within a common database so that any spacecraft component or external system can query that repository for specific characteristics and then subscribe to that component's capability or service. A similar model is under development by the Consultative Committee for Space Data Systems (CCSDS) called the Spacecraft On-board Interface Services. NASA and international space agencies are currently looking into this approach, and the ORS Office plans to collaborate with both NASA and CCSDS to achieve a standard consensus-based approach for future interoperability.

SPA interface standards also enable the adoption of a modular panel architecture that employs quick panel-to-panel electrical/mechanical interconnects. This allows rapid assembly of a variety of structural configurations suitable for responding to the expected range of ORS missions using a smaller set of standard panels as "building blocks." SPA standardizes the mechanical mounting of components to the bus structure. Standardized connection nodes are freely locatable on panels and can provide power service or SPA device ports for connecting SPA-compliant components with SPA-specified harnessing.

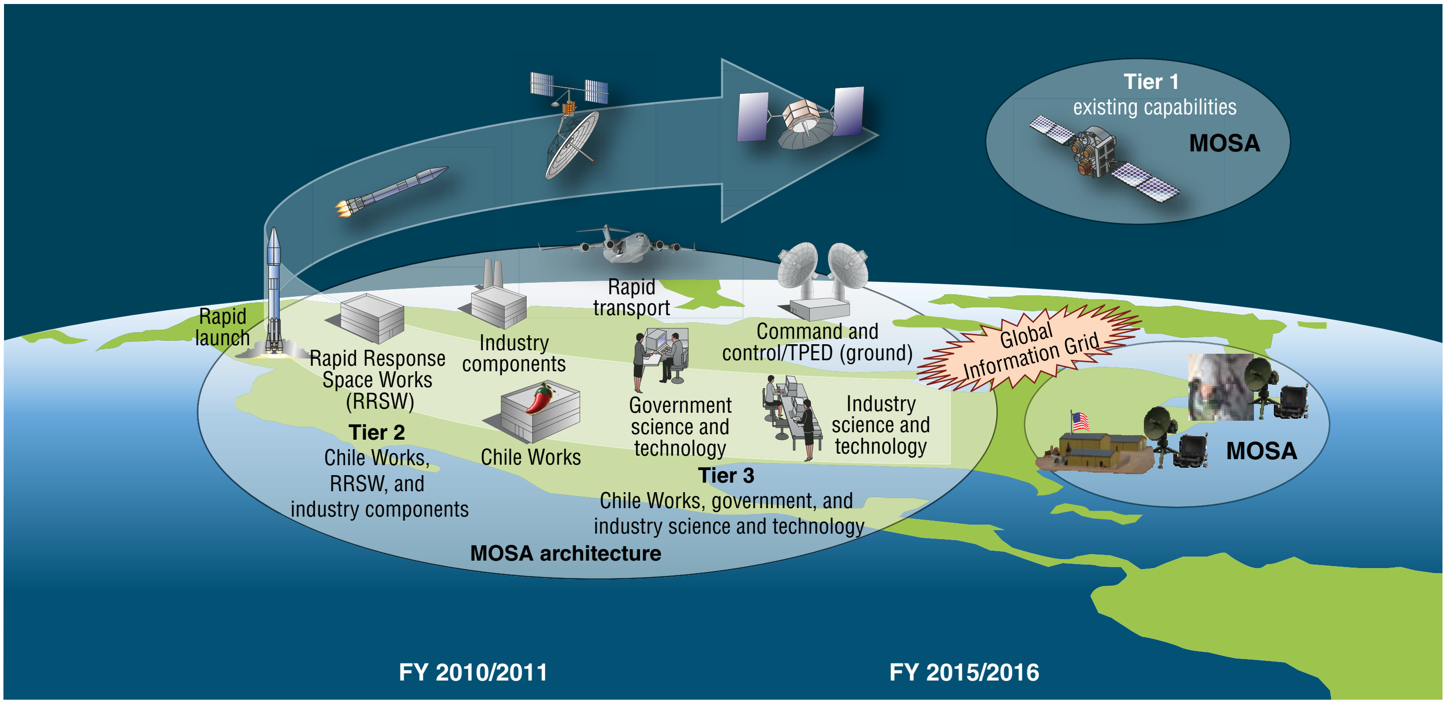
An underlying requirement to optimize performance for a reconfigurable multimission bus is a Mission Design Tool (MDT). An MDT will provide mission design and systems engineering for defining new mission configurations for rapid assembly from common building blocks (panels, components, and software modules). The MDT will maximize the efficiency of the multimission bus with its hosted payload in terms of on-orbit dynamics, mass properties, and thermal management. Although specific mission performance can be optimized through limited modularization of the payload, power storage/collection, attitude control, software, telecom, and propulsion subsystems, the inclusion of the SPA plug-and-play interfaces and architecture enables modularity to the piece part level for nearly complete system reconfigurability.

In the near term, ORS spacecraft architectures must support the integration of both SPA and legacy components. For legacy interfaces, the self-discovery function supporting the rapid integration process requires the inclusion of a SPA standard adapter called the Appliqué Sensor Interface Module. This module provides the specific hardware and software to adapt the legacy device interface for the SPA protocol, and can eventually be removed from the spacecraft as future component developers adopt the SPA or equivalent standard into their developments.

The ORS Office has concluded that adapting the ISET and SPA standards into the spacecraft architecture and RRSW operation along with adopting the standards currently used by the C2/TPED and launch communities represents the most effective means for the ORS Office to operate like a U-2 Wing while supporting fast and seamless integration into existing theater operational architectures.

Summary

An agile space environment represents the most viable strategy for responding to the broad post–Cold War spectrum of risk within a rapidly changing technology-driven world. Increased operations tempo and diminishing budgets are driving the national security space community to pursue more flexible and economical means of responding to global threats. Open architectures and standards clearly enable more flexible and timely responses to warfighter



Crawl phase

- Mature Tier 1 and Tier 3 capabilities
- Demonstrations with Tier 1 and 3 to develop/exercise concept of operations
- Develop the "Chile Works"
- Adopt/adapt initial MOSA standards

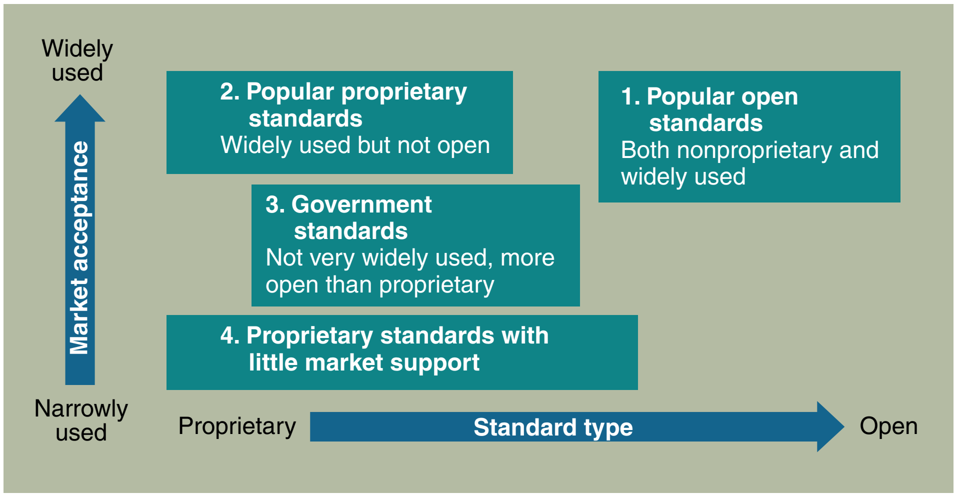
Walk phase

- Tier 2/3 initial operational capability in Chile Works
- Use Chile Works to provide and mature Tier 2 capability

Run phase

- Transition Tier 2 rapid assembly, integration, and test capability to RRSW (enabled by MOSA standards)
- Maintain Tier 3 at Chile Works for technology refresh/insertion
- Maintain/evolve MOSA

The Operationally Responsive Space Office is working to deliver an end-state operational capability that can respond to joint force commander needs in minutes (Tier 1), days (Tier 2), or within a year (Tier 3). A modular and open systems approach (MOSA) represents the most effective means to evolve and maintain a responsive space capability that can rapidly deploy space capabilities with seamless integration into existing theater operational architectures.



The ORS Office strategy for selection of standards is to "adopt, adapt, and as a last resort develop." This diagram illustrates the priority by which the ORS Office adopts or adapts standards.

needs with their ability to more rapidly incorporate the latest technological advances while reducing development and operational costs.

Achieving open architectures and standards for space is not without challenges. The low market volume that characterizes the existing environment for space systems makes it unpalatable for the space industry to invest in significant, nonrecurring expenses and adopt modular and open architectures without expecting a sufficient return on investment. Getting the space industry on board with these standards requires commitment from the broader government community. On the other hand, government commitment requires adequate demonstration of these new architectures and standards to instill confidence, establish flight heritage, and address mission assurance. Rapidly demonstrating new architectures and standards for exquisite systems that require higher mission assurance is just not possible within current acquisition budgets and timelines. The ORS Office may be able to provide a solution to this "chicken and egg" problem. It offers the broader space community an economical and low-risk proving ground to quickly gain flight heritage for new open architectures and standards that can equally enable the objectives of "good enough" or "exquisite" space capabilities.

Although driven to deliver assured space power that is focused on timely satisfaction of JFC needs, the ORS Office also offers an opportunity for collaboration across the greater space community that is focused on mutually beneficial architectures and standards that support overall rapid response, innovation, and reduced costs.

The ORS Office conducted several demonstrations using the Space Plug-and-Play Avionics (SPA) standard-enabled spacecraft developed by the Air Force Research Laboratory at Kirtland Air Force Base, New Mexico. These demonstrations helped define an early baseline of processes, metrics, and lessons learned for defining the prototype Rapid Response Space Works called "Chile Works." Technicians were able to assemble a fully functional plug-and-play bus (shown) from its component piece parts in less than four hours.

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Courtesy of NASA

Agile Space Launch

Aerospace has been providing systems engineering support to the Space Test Program, the Operationally Responsive Space Office, and the Air Force Research Laboratory, in an effort to rapidly launch and deploy satellites in the evolving agile space environment.

Steven Weis and Lisa Berenberg

Agile launch is one component required to support the goals of the Operationally Responsive Space (ORS) Office, whose mission is to rapidly augment DOD space systems to support the warfighter in near real time. For ORS, "rapidly" is defined as mission call-up to launch in a matter of days or weeks. The target launch time for augmentation missions is six days. Typical DOD missions currently take years and even decades to become operational on orbit, so the ORS goal is an ambitious one. Agile space launch involves planning, acquiring, and executing a launch quickly, but more than that, it requires flexibility in mission design, availability of multiple spacelift options, and a readiness to seize opportunities.

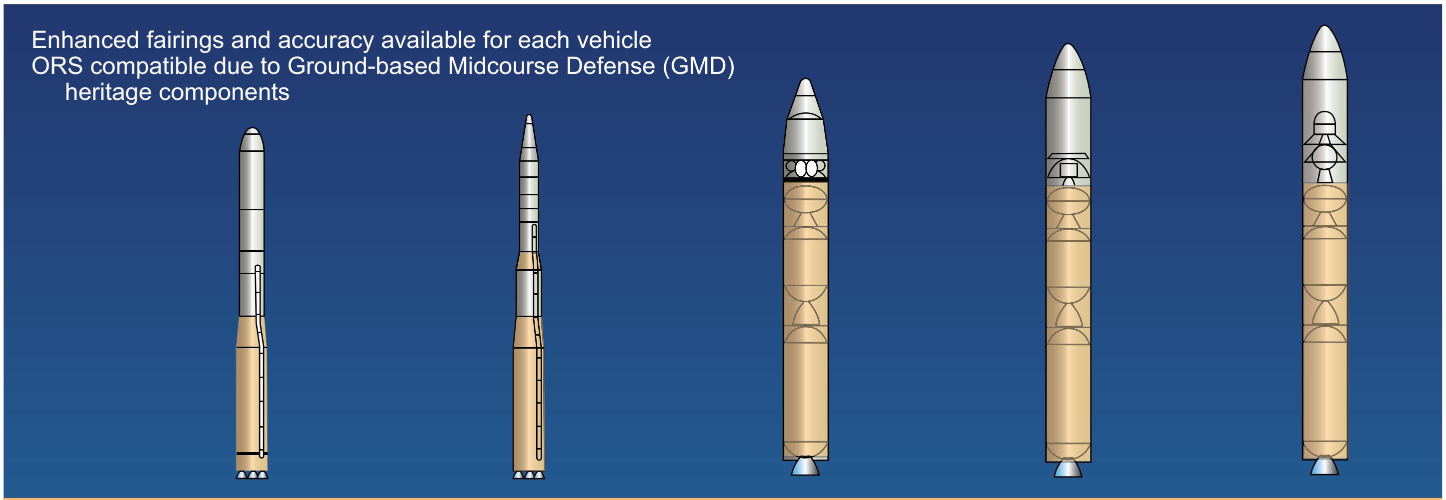
The Aerospace Corporation has provided systems engineering support to the ORS Office since its founding in May 2007. Aerospace has also provided systems engineering and mission assurance support to the DOD Space Test Program (STP) since its inception in 1965. STP is the primary provider of mission design, spacecraft acquisition, integration, launch, and on-orbit operations for DOD space experiments and technology demonstrations. The typical mission timeline is three years from start to on-orbit operability, and for two recent missions, the timeline was under 12 months from call-up to launch.

These two recent missions, Kodiak Star and Nanosat-2, illustrate the successful application of the principles of agile space launch. For the Kodiak Star mission, STP and NASA, in approximately 11 months, identified and prepared a payload to fly aboard the Athena I launch vehicle. The Nanosat-2 spacecraft, in storage for a year, was reconfigured in four months to fly on the Delta IV heavy-lift vehicle demonstration in 2004.

These two launches, as case studies, provide valuable insights into how to reach the ambitious launch goal of six days. For both missions, Aerospace was a key member of a small team that provided systems engineering support directly to the Air Force mission manager, and then supported the readiness review process with a mission risk assessment to the Air Force mission director.

A survey of current launch vehicles that endeavor to have a "rapid" launch capability is also useful in understanding how far the industry must come to meet the six-day goal. For example, the Minotaur family of vehicles, which use surplus ballistic missile components, provides low-cost, reliable space launch capability to meet U.S. government small-satellite requirements. The Falcon 1 and Raptor series launch vehicles provide additional launch options for small payloads from STP and other DOD programs. Aerospace was a member of the government team developing the payloads that flew on the eight Minotaur missions to date and is involved at varying levels in five of the seven Minotaur missions next scheduled for flight.

STP is also working to use the excess capability—the additional launch vehicle performance and volume margin not used by the primary mission—on launches of government Evolved Expendable Launch Vehicles (EELV) to fly both research and operational payloads. Aerospace was instrumental in the design and development of the EELV Secondary Payload Adapter


Enhanced fairings and accuracy available for each vehicle
ORS compatible due to Ground-based Midcourse Defense (GMD) heritage components

	Minotaur 1	Minotaur 2	Minotaur 3	Minotaur 4	Minotaur 5
S1	M55A1 (GFE)	M55A1 (GFE)	SR-118 S1 (GFE)	SR-118 S1 (GFE)	SR-118 S1 (GFE)
S2	SR 19 (GFE)	SR 19 (GFE)	SR-119 S2 (GFE)	SR-119 S2 (GFE)	SR-119 S2 (GFE)
S3	Orion 50XL	M57 (GFE) (Orion 50XL optional)	SR-120 S3 (GFE)	SR-120 S3 (GFE)	SR-120 S3 (GFE)
S4	Orion 38	(N/A)	Super HAPS	Orion 38 (Star 48BV optional)	Star 48BV
S5	HAPS (Optional)	(N/A)	(N/A)	HAPS (optional)	Star 37FMV
Application	***Spacelift***	***Suborbital/target***	***Suborbital/target***	***Spacelift***	***MTO/GTO/Lunar***
Performance	581 kg to LEO Larger fairing optional	441 kg ballistic (524 kg w/ Orion 50XL) Larger front end optional	3064 kg ballistic Larger fairing optional	1636 kg to LEO (1931 kg w/ Star 48BV)	700 kg to MTO (GPS) 584 kg to GTO 392 kg to TLI

LEO=185 km, 28.5°
Ballistic=VAFB to RTS

Above: The Minotaur 1 through 5 vehicles with their corresponding application and performance information. Aerospace was a member of the government team developing the payloads that have flown on the eight Minotaur missions to date and is involved at varying levels for flights of five more scheduled for launch. *Previous page*: An Athena 1 launch vehicle lifts off the launchpad at Kodiak Launch Complex with the Kodiak Star spacecraft onboard Sept. 29, 2001.

(ESPA) and supported its demonstration flight on the STP-1 mission in March 2007.

With this new effort to pursue the tenets of agile space that will reduce the timeline for spacelift from years to days to support the ORS mission, benefits to the entire U.S. space industry could be realized, including a reduction in costs, a standardization of interfaces, and a streamlining of processes.

Responsive Payloads: Two Case Studies

Kodiak Star

The Kodiak Star mission launched in September 2001 provides a useful case study in responsive mission design and interagency collaboration. Originally scheduled for August 2001, the mission was supposed to be the first orbital launch from the Kodiak Launch Complex on Kodiak Island, Alaska. However, NASA's primary payload, the Vegetation Canopy Lidar, had been canceled because of developmental problems. NASA needed a replacement—one that could be ready soon enough to maintain the launch date. At an industry conference in August 2000, representatives of NASA's Expendable Launch Vehicle office met with members from the STP mission design office to discuss a possible solution. Within a month of this first meeting, NASA and STP had identified four spacecraft that could meet the orbital constraints and tight schedule: Starshine 3, PICOSat, PCSat, and SAPPHIRE.

Starshine 3 (Student Tracked Atmospheric Research Satellite Heuristic International Networking Experiment), developed by the Rocky Mountain NASA Space Grant Consortium and the Naval Research Laboratory, was a one-meter sphere covered with approximately 1500 aluminum mirrors. Students throughout the world would track the satellite through the glinting of sunlight off the mirrors and publish the data collection over the Internet. When it was proposed for the Kodiak Star mission, completed mirrors were available, but the main structure had yet to be manufactured.

PICOSat, built by Surrey Satellite Technology Ltd. of the United Kingdom for STP, flew four scientific payloads, including one provided by the Aerospace Space Science Applications Laboratory. When it was selected for the mission, the satellite was completely assembled and tested and waiting for a launch opportunity. Partially funded by the Office of the Secretary of Defense Foreign Comparative Test Office, PICOSat demonstrated the viability of using a commercial-off-the-shelf microsatellite platform to provide cost-effective and timely access to space for DOD space experiments. Aerospace provided systems engineering support to STP throughout the development and testing of PICOSat, maintained continuity during the transitions between Air Force program managers, and ultimately assumed day-to-day management responsibility of PICOSat because of Air Force personnel shortfalls.

The other two STP-sponsored spacecraft aboard Kodiak Star had an educational component and were used to train students in spacecraft operations. The first, PCSat (Prototype Communications Satellite), was designed, built, and tested by midshipmen at the United States Naval Academy. It was still in the design stage when it was selected for the mission. The second, SAPPHIRE (Stanford Audio Phonic Photographic Infrared Experiment), was built by students at Stanford University, with preflight integration and postlaunch operations support provided by Washington University in St. Louis.

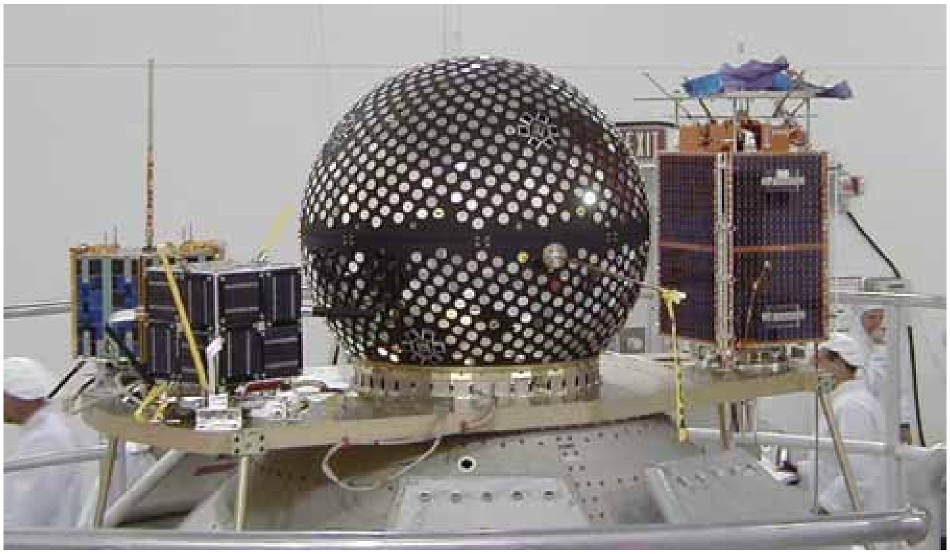
Like PICOSat, SAPPHIRE was "on the shelf," waiting for a launch opportunity. For these student-built spacecraft, Aerospace worked with the spacecraft teams to identify risks and implement mitigation plans to keep the mission on schedule, and provided technical assistance in the development and verification of the requirements in the interface to the launch vehicle.

To adapt the existing launch vehicle hardware to fly the four new spacecraft, Lockheed Martin designed, manufactured, and tested a unique payload upper deck for the Athena I in just five months to support the spacecraft fit check in March 2001. Lockheed Martin also wrote new flight software to allow the launch vehicle to deploy the three STP satellites into an 800-kilometer orbit, then maneuver into a 500-kilometer orbit for the release of Starshine 3.

Each spacecraft, after completing environmental testing, was delivered to the payload processing facility at the Kodiak Launch Complex and integrated onto the payload upper deck starting the final


Courtesy of Boeing

The Delta IV heavy completed a demonstration flight from Cape Canaveral in December 2004, carrying the student-built Nanosat-2. The launch vehicle did not reach the intended orbit, so Nanosat-2 was unable to complete its science objectives.


Courtesy of NASA

The Kodiak Star spacecraft is readied for encapsulation in the fairing as it is prepared for launch. The payloads aboard this mission included the Starshine 3, sponsored by NASA, and the PICOSat, PCSat, and SAPPHIRE, sponsored by the Department of Defense Space Test Program out of Albuquerque, New Mexico.

week in July 2001. Aerospace supported the launch site activities for all three of the STP-sponsored spacecraft, and provided on-console support to the Air Force mission manager during launch operations. After a series of terrestrial and space weather delays, and travel limitations imposed in the aftermath of September 11, launch of the Kodiak Star mission occurred on September 29, 2001, with the launch vehicle achieving the desired parameters for both targeted orbits.

Nanosat-2

The Air Force Space and Missile Systems Center (SMC) tasked STP in June 2003 to investigate the feasibility of flying an auxiliary payload on the EELV Delta IV heavy demonstration, scheduled to launch in June 2004. Nanosat-2 was ultimately selected. Nanosat-2 had originally been planned to launch aboard the space shuttle in the Shuttle Hitchhiker Experimental Launch System, but after significant delays in the shuttle manifest, Nanosat-2 was put into storage to await other flight opportunities.

Nanosat-2, actually a stack of three space vehicles, was developed under the University Nanosatellite Program, a joint program of the Air Force Research Laboratory, the Air Force Office of Scientific Research, and the American Institute of Aeronautics and Astronautics. Constructed by student teams at the University of Colorado, New Mexico State University, and Arizona State University, Nanosat-2 was designed to demonstrate two different low-shock separation systems for small satellites and perform collaborative formation flying. All three spacecraft and the associated interface hardware had been assembled and tested when selected for the demonstration.

After call-up on January 23, 2004, the satellite had four months until it had to be mated to the DemoSat, the main payload of the mission. After an initial kickoff meeting with the mission team, including the government agencies and contractors representing both the satellite and launch vehicles, the Nanosat-2 stack was reduced from three spacecraft to two. Satellite and launch-vehicle work began immediately. The satellite was refurbished and cleaned February 2–25 and reassembled February 26–27; electrical checks were completed March 8–12. Meanwhile, the launch vehicle team was developing a one-of-a-kind adapter to mount the satellite to the DemoSat, designing unique mechanical, electrical, and environmental interfaces.

On March 29, the launch vehicle interface requirements were completed, and the satellite began testing to the new requirements. Random vibration and sine tests were conducted April 5–9, electromagnetic interference testing April 14–23, and shock testing May 3–7. Nanosat-2 was mated to DemoSat May 3–7, and on June 28 encapsulation inside the fairing was completed. The Nanosat-2 team managed to go from storage to mate in 115 days, with approximately half that time spent waiting for the definition of the interface for the launch vehicle.

During this four-month effort, Aerospace served as the systems engineering liaison between the Air Force Research Laboratory and the launch vehicle contractor, with personnel from what is now the Space Innovation Directorate supporting STP and personnel from the Launch Operations Division supporting the Air Force Launch and Range Systems Wing.

After the physical integration was completed, the Aerospace focus shifted to mission assurance, with an emphasis on ensuring that the presence of the nanosat payloads would not adversely affect the primary goal of the Delta IV heavy-lift demonstration mission. Particular emphasis was placed on the qualification of the satellite and the robustness of the separation system, including a new separation-signal timer box. After a thorough Aerospace review, including the requirement for additional separation system ground testing, Aerospace deemed the nanosat system low risk for launch.

The Delta IV heavy demonstration was launched December 21, 2004. During launch, sensors in the Delta IV common booster cores incorrectly registered depletion of propellant, resulting in a premature shutdown of all three stage-one engines and a significant performance shortfall. Nanosat-2 was successfully separated from DemoSat, but in a lower orbit than expected, and was unable to complete its remaining science goals.

Responsive Launch Vehicles

Minotaur

Orbital Sciences Corporation, under the U.S. Air Force Orbital/Suborbital Program contract, develops and provides launch services for government-sponsored payloads using a combination of government-supplied Minuteman and Peacekeeper rocket motors and commercial launch technologies. The use of surplus ICBM assets significantly reduces launch costs while leveraging the heritage of proven systems.

Orbital's Minotaur I is a four-stage launch vehicle using surplus Minuteman solid rocket motors for the first and second stages, combined with the upper-stage structures and motors originally developed for Orbital's Pegasus XL vehicle. Minotaur I can launch payloads up to 580 kilograms into low Earth orbit, and has had 100-percent success after eight missions.

Minotaur IV uses the three solid rocket motor stages from the Peacekeeper ICBM and a commercial solid rocket upper stage to place payloads up to 1730 kilograms into low Earth orbit. The first flight of Minotaur IV is scheduled for 2009. Minotaur V is a five-stage derivative of Minotaur IV using two commercial upper stages to launch small spacecraft into high-energy trajectories.

The Minotaur launch vehicles have a standard 18-month procurement cycle. Studies show this cycle could be reduced to 12 months without any new processes or hardware; however, this is still a 52-week cycle, as opposed to the one-week ORS target. Additional reductions in schedule are being investigated,

Courtesy of U.S. Naval Academy

PCSat-1 (Prototype Communications Satellite) was built at the U. S. Naval Academy with student participation throughout its development. The mission demonstrated a low-cost approach to satellite design. PCSat-1 completed its eighth year in orbit in Sept. 2009.

including ideas such as “stockpiling,” where the launch vehicle is completely assembled and tested and just awaits a spacecraft; automating mandatory analyses such as coupled loads and range-safety corridor development; and using dedicated personnel—possibly Air Force personnel—to perform the work required to launch a mission on a “24/7” basis. Aerospace is helping the ORS Office evaluate contractor studies.

Falcon 1

To provide additional launch options for small spacecraft, the Air Force also has the Responsive Small Spacelift program, designed to provide military customers with low-cost, responsive (12 to 18 months) commercial launch services. Three launch vehicles are available on the contract: Falcon 1, Raptor I, and Raptor II.

SpaceX (Space Exploration Technologies Corporation) is developing the Falcon family of low-cost, liquid-fueled launch vehicles. Falcon 1 is a two-stage launch vehicle, which, in September 2008, became the first privately developed liquid-fueled rocket to orbit Earth. The first stage is powered by a single regeneratively cooled Merlin 1C engine developed by SpaceX. The primary structure uses a SpaceX-developed flight-pressure-stabilized architecture, which has high mass efficiency relative to traditional structures while avoiding the ground-handling difficulties of a fully pressure-stabilized design (some rockets, such as the Atlas II, are unable to support their own weight on the ground and have to be pressurized to hold their shape). The second stage is powered by a single Kestrel engine, also developed by SpaceX.

Launched from SpaceX’s launch facility in the Kwajalein Atoll, Falcon 1 can place up to 420 kilograms into low Earth orbit. An enhanced version, Falcon 1e, with estimated availability beginning in 2010, will be capable of launching payloads weighing up to 1010 kilograms.

From the beginning of the Falcon program, SpaceX has advocated a streamlined process for spacecraft integration and interface analyses through standardization and limiting the analysis cycle to one iteration—the verification cycle when all the models are mature. These ideas should continue to reduce the Falcon I integration cycle to bring it closer to the ORS goal.

Raptor

Also available on the Responsive Small Spacelift contract are two air-launched vehicles, Raptor I and Raptor II, built by Orbital Sciences. Raptor I, derived from the Pegasus XL, is dropped from Orbital’s L1011 “Stargazer” aircraft, providing the flexibility to launch from worldwide locations with minimal ground support requirements. Like Pegasus XL, Raptor I is a winged, three-stage solid rocket booster capable of delivering up to 475 kilograms into low Earth orbit. Raptor II is an air-launched version of Orbital’s three-stage Taurus-Lite launch vehicle. Flown to the launch location inside a C-17, the Raptor II is extracted from the aircraft, slowed and stabilized using a parachute system, and ignited in a nearly vertical position. It can deliver up to 250 kilograms to low Earth orbit.

Since both Raptor vehicles are air-launched, they can achieve low-inclination orbits and can potentially reduce cycle time by removing the constraints of ground-based range infrastructure. The use of air-launched vehicles is being studied closely by the ORS Office to see what advantages they may have over ground-based launchers.

The STP-1 payload stack being encapsulated at Astrotech in Titusville, Florida.

EELV Secondary Payload Adapter

As early as 1997, STP and the Air Force Research Laboratory began developing the capability to fly up to six auxiliary payloads on Atlas V and Delta IV. The result was the EELV Secondary Payload Adapter (ESPA), first flown on the STP-1 mission in March 2007. Aerospace was part of the ESPA development team from the concept stage, providing systems engineering and mission assurance support.

The ESPA is installed below the primary payload to provide rideshare opportunities for 180-kilogram spacecraft that fit inside a volume of 24 × 28 × 38 inches. This mass and volume constraint has now become known as the “ESPA class.” To simplify the inclusion of the ESPA on future missions, STP, the EELV program office, and United Launch Alliance are working to develop a standard service option for government launches. This service would include all of the necessary interface hardware (ESPA ring, auxiliary payload separation systems, and harnessing) along with the required mission integration analyses.

Enablers for Future Agile Space Launch

Changes to the Mission Design Paradigm

The standard integration timeline for small launch vehicle missions is 12 to 18 months from contract award to initial launch capability. This schedule is driven primarily by the launch vehicle hardware procurement cycle, and to a lesser extent, by the design methodology used on most missions. Advanced procurement of long-lead items can accelerate the hardware delivery, but accelerating the mission integration timeline requires a change in philosophy.

The standard mission design methodology selects a launch vehicle while the spacecraft is still in the preliminary design phase based on its expected final mass and desired orbit. The spacecraft is then designed to meet the specifications of the selected launch vehicle and to survive the launch environments. This paradigm greatly limits the ability to change the mission should the need arise.

Kirk Nygren and Lisa Berenberg with the Nanosat-2 payload mated to the Demosat as it is prepared for launch on the Delta IV heavy demo vehicle.

A more agile approach incorporates innovative design practices on both the spacecraft and launch vehicle sides of the interface. Designing and testing a spacecraft to levels that envelop multiple spacelift options would provide more flexibility in launch manifesting. For example, Nanosat-2 had been tested to space shuttle requirements, giving confidence that it could survive on the EELV Delta IV heavy. SAPPHIRE was designed and tested to be compatible with almost any potential launch option.

Changes to Spacecraft Systems

STP has embraced this new paradigm in the procurement of the so-called Standard Interface Vehicle—essentially a generic spacecraft bus with a standardized payload interface. The Standard Interface Vehicle contract was for the purchase of up to six space vehicles that would be compatible with five different launch vehicles—the Minotaur I and IV, Pegasus, and the Delta IV and Atlas V ESPA. This allows for "next available opportunity" manifesting.

Designing a spacecraft to multiple launch vehicle standards allows it to be built and "put on the shelf." The approach is clearly feasible: two of the four satellites on the Kodiak Star mission (SAPPHIRE and PICOSat) and the Nanosat-2 spacecraft were complete and ready for the next available launch opportunity.

Still, there are drawbacks to this "satellite-on-the-shelf" approach, such as component degradation, continuous testing requirements, and technology obsolescence, to name a few. To combat these issues, the Air Force Research Laboratory has come up with an innovative spacecraft design and manufacturing concept known as plug-and-play. Analogous to the home personal computer, where all the components fit together regardless of the manufacturer through the use of a common interface (the USB, or universal serial bus), the plug-and-play satellite program has developed a standard interface for all the avionics on the bus. Through the use of this interface, components can be kept on the shelf, and by using a dedicated space-vehicle integration facility, a unique satellite that meets mission requirements can be designed and assembled in six days.

Changes to Launch Systems

Once the issue of standardization of physical interfaces is resolved, additional changes to launch-vehicle systems will be required to meet the six-day launch goal. As with satellites, one way to meet the six-day goal is to build the launch vehicle and then place it in storage to await a payload. Drawbacks to this concept are not hard to imagine, including the significant investment in explosive storage requirements and the testing and component life issues similar to those of the satellites. However, even with this stockpiling of launch vehicles, numerous preparations remain, such as the development of the flight software to fly the correct trajectory to the correct orbit, analysis of coupled loads to ensure no structural coupling between the satellite and launch vehicle, and development of guidance and control algorithms, to name a few.

These preparations currently must be done serially, starting with coupled loads analysis, then guidance and control, and then flight software; the process takes about three months. The introduction of automated software development tools could bring this cycle time down to days, and is absolutely necessary for the ORS Office to meet its goals.

Changes to Launch Range Infrastructure

The last piece of the launch timeline, and the one that has not been addressed by any missions to date, is that of range infrastructure—specifically in the area of flight safety. The range infrastructure required to launch national space systems is very extensive; thus, in the United States there are only two ranges that launch national security space missions—Cape Canaveral in Florida and Vandenberg in California. One way to limit the range interface timeline would be to remove a mission from the range, but though that may save some time in the areas of ground interfaces, flight safety must always be ensured. Studies in this area are in their infancy, and the conclusions of these studies will be reviewed carefully.

Agile Space—A Multifaceted Issue

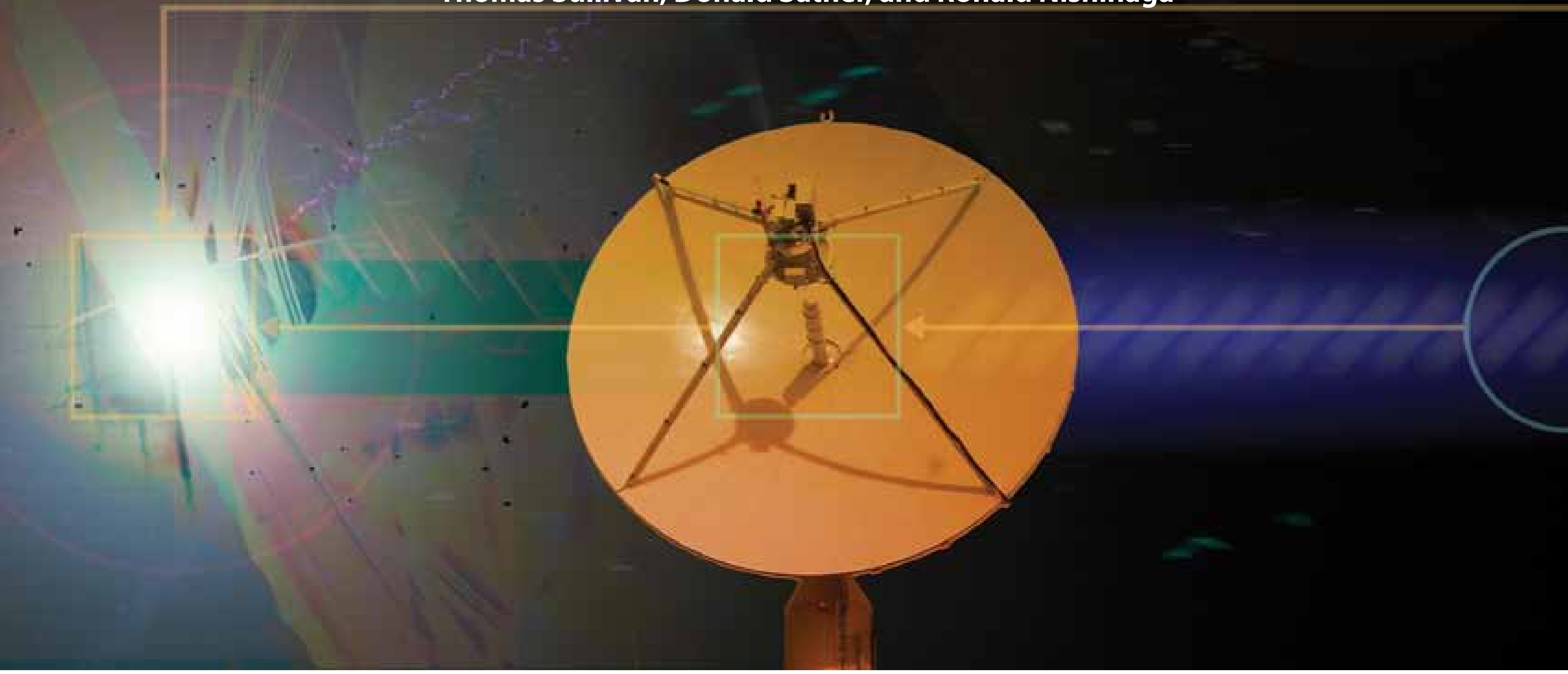
The three military offices at Kirtland Air Force Base in New Mexico—STP, the Air Force Research Laboratory, and the ORS Office—are working together to define solutions to the ORS goal of a six-day mission timeline. The concept of agile launch implies it is not a single mission component that will meet this ambitious goal, but rather a collection of innovations across all mission components—spacecraft, launch vehicles, and launch ranges—and across all engineering disciplines—mechanical and electrical interfaces, software, and systems engineering.

In supporting all of these offices, Aerospace is uniquely positioned not only to ensure coordination across the effort, but to help define the architecture of the effort. Various government and industry organizations have been considering components of agile launch for years, but the ORS mission has only been codified for two years; so, the effort is really in its infancy. In the future, the ORS Office may transform some of the tenets of agile launch discussed in this article into flight demonstrations, and when that happens, it may well revolutionize the way space missions are conceived and executed.

A Flexible Satellite Command and Control Framework

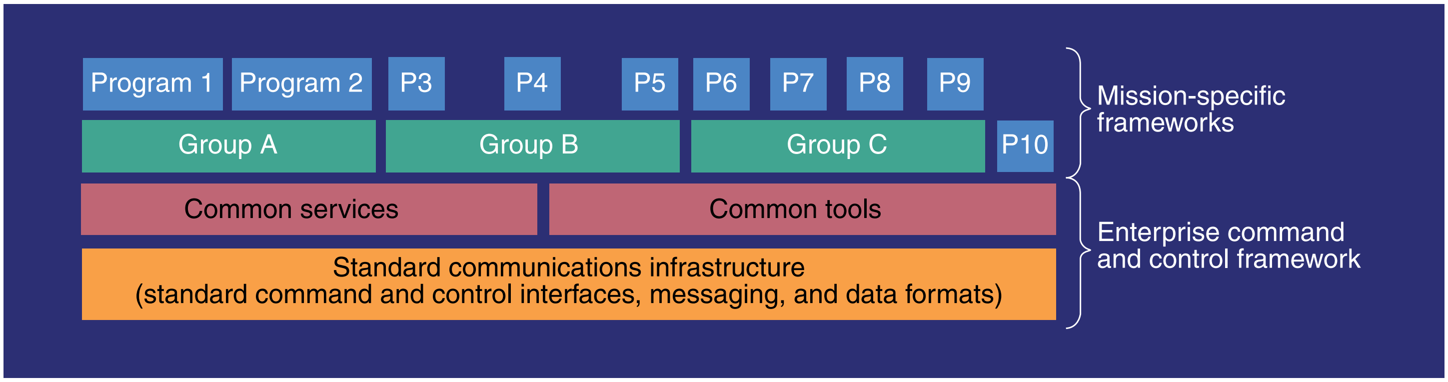
A standard communications infrastructure and shared services allow for rapid receiving and publishing of mission information using common message and data standards, thus enabling situational awareness along with reduced operation and maintenance costs.

Thomas Sullivan, Donald Sather, and Ronald Nishinaga



The Air Force Space and Missile Systems Center (SMC) Satellite Control and Network Systems Group has been exploring concepts for future satellite command and control implementations. The studies have examined how to apply advances in information technology to improve interoperability, responsiveness, and economy. From these studies, a vision has emerged for an extensible or "compatible" framework that is beginning to shape the future direction of satellite command and control procurement and concepts of operation within SMC.

A framework can be defined as a common system (hardware and software) architecture that a given enterprise is built upon. It selectively constrains the design of the enterprise overall and the individual elements or missions within it. A framework can be created as a service-oriented, netcentric, bus-based, or object-oriented architecture, or any combination of these. One advantage of the framework approach for command and control is that it accommodates a flexible ground infrastructure to support rapid deployment of space assets for tactical space missions. Not surprisingly, the DOD Operationally Responsive Space (ORS) Office has been investigating how such an approach could be used to meet responsive space requirements.



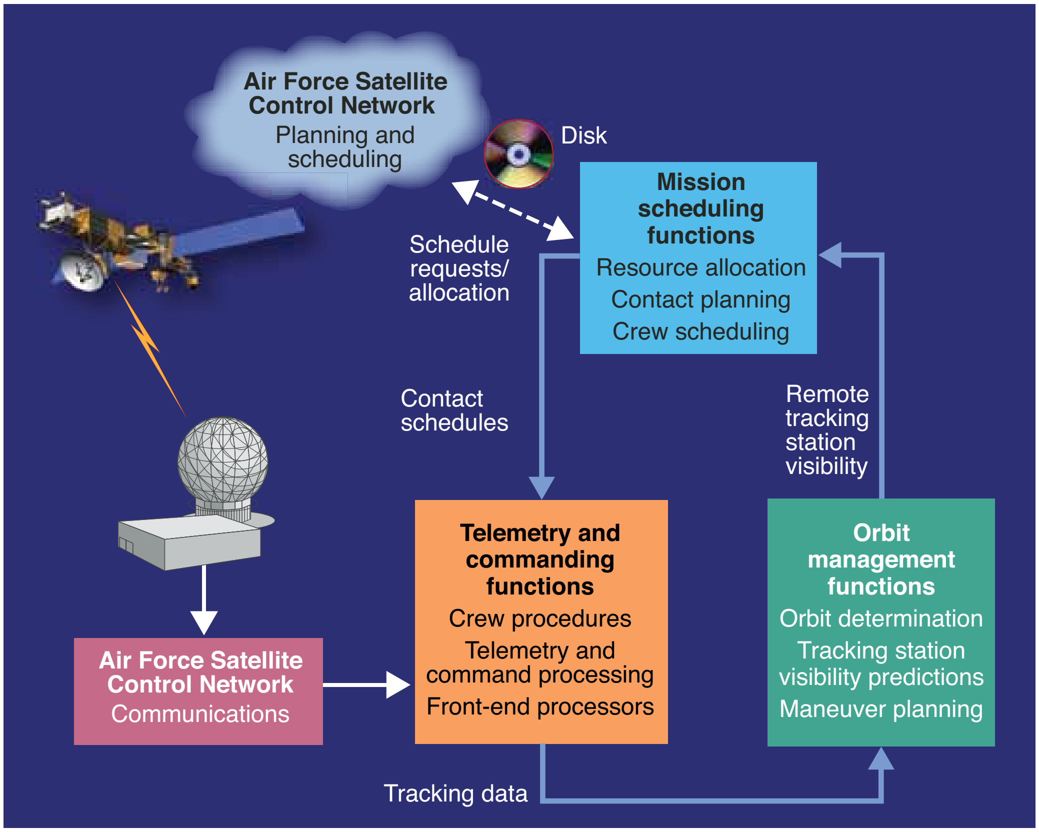
A framework is the common hardware and software system architecture that an enterprise is built upon. A framework selectively constrains system design for specific missions, and can be created as a service-oriented architecture, netcentric, bus-based, object-oriented, or any combination of these or any other architecture. Here, mission-specific frameworks and enterprise command and control frameworks are grouped with various programs, common services, and common tools.

The Aerospace Corporation's Ground Systems Laboratory in Chantilly, Virginia, has been working closely with SMC's Satellite Control and Network Systems Group and the ORS Office on these projects. Aerospace has concluded from initial studies that the concept of a compatible command and control framework is technically viable for Air Force satellite tracking, telemetry, and commanding operations.

History of Air Force Satellite Command and Control

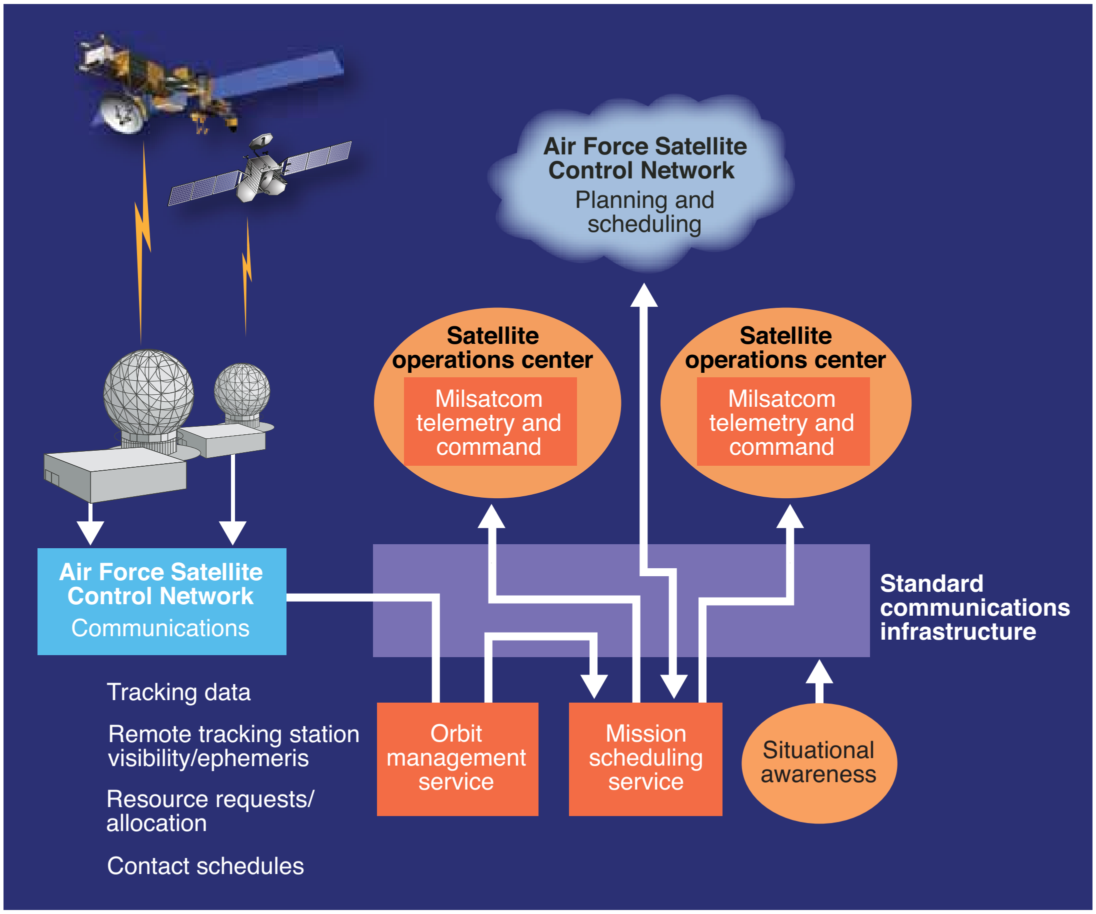
The Air Force Satellite Control Network (AFSCN) is a network of ground remote tracking stations and control nodes that support the launch, command, and control of various national security space assets. The two operational control nodes, located at Schriever Air Force Base in Colorado Springs and Onizuka Air Force Station in Sunnyvale, California, provide the communication relays and resource management that enable the satellite operations centers to interact with remote tracking stations around the globe. The operational control nodes at Schriever and Onizuka started as dedicated ground systems for processing mission data and state-of-health data; they were based on IBM mainframe technologies developed in the 1970s. In the 1980s, AFSCN started using a common system architecture for satellite telemetry, tracking, and command. This architecture, originally known as the Data Systems Modernization, eventually became known as the Command and Control Segment. The Air Force achieved early successes with this architecture, which eventually spread to multiple satellite programs. However, each program still had to employ mission-unique functions on the common architecture, and these became difficult and expensive to maintain or upgrade as more advanced satellites came online.

In the 1990s, the Air Force attempted to replace the Command and Control Segment with the Standardized Satellite



A typical satellite operations information cycle. One portion of the information cycle for satellite operations includes the continuous stream of tracking data from daily satellite contacts that is needed by orbit management personnel to determine future satellite position information. In turn, this position information is used to determine AFSCN tracking station service opportunities in the future that mission planning personnel use to schedule satellite contacts that accomplish specific satellite mission and maintenance functions. The cycle repeats as each planned satellite contact is executed by satellite operators performing telemetry analysis and commanding functions that, in turn, generate new tracking information.

Control System, but ended the effort because the business case did not support its development and its schedule became extended so that it could not support the needs of the individual programs. Instead, each individual satellite program was directed to begin procuring its own telemetry, tracking, and commanding solutions. As a result, "stovepipe" systems were developed for each mission area, which still exist today (e.g., Milsatcom, navigation). This approach duplicated common ground system functions and created unique user interfaces, which made training less standard. Stovepipe systems do have an advantage in that they effectively meet the specific needs and timelines of each satellite program; however, they are not interoperable, and they have become expensive to maintain over time.



A compatible satellite command and control framework enables multiple operations centers to share a common set of tools and services that are added to the infrastructure over time as appropriate. Each mission can also build mission-specific components on top of the shared enterprise framework. Legacy systems can interface with the common infrastructure too.

Flexible Command and Control Framework

Unlike the stovepipe approach, the envisioned command and control framework is a standard, open communications infrastructure based on commercial networking technologies. It provides common physical interfaces for communications protocols within and among satellite operations centers and shared antenna resources provided by AFSCN. It is built upon a core set of specific standards for messaging and for formatting the data transported by those messages, which represent satellite operational information (e.g., telemetry, commands, orbits, mission activities).

This framework enables multiple operations centers to share a common set of tools and services that are added to the infrastructure over time as appropriate. Each mission area can also build mission-specific components on top of the shared enterprise framework. At a minimum, legacy systems can interface to the common infrastructure to provide access to their satellite command and control information, and can begin migrating to those common tools and services that provide the best return on investment. New satellite programs would be designed to use the shared infrastructure, and only those command and control elements that are unique to each mission would have to be built, thereby reducing overall system cost.

Concepts of Operation Flexibility

The envisioned command and control framework accommodates multiple concepts of operation without changing its fundamental standards. For example, when implemented for a single satellite mission, it provides a predeveloped infrastructure and set of core services that require additional development of only the mission-unique portion of the ground-control software. It does not constrain satellite missions to specific services; rather, it enables a program to tailor its uses of the framework to best meet its specific requirements. To fit into the framework, a satellite mission must adhere to the standards for messaging and data between the command and control functions it creates. Doing so avoids the rigid, one-size-fits-all approach that made the Data Systems Modernization architecture inflexible and costly to change.

Another possibility is to use the framework within a multimission operations center, where each individual satellite mission shares a common infrastructure. Each mission has its own unique piece, but all missions can use the shared services provided in the framework for common command and control functions. Extending the framework across multiple satellite operations centers creates a true enterprise for satellite operations, where multiple centers can share a

> *New satellite programs would be designed to use the shared infrastructure, and only those command and control elements that are unique to each mission would have to be built, thereby reducing overall system cost.*

Architecture Principle	Definition	Actions
Utility	• The measure of usefulness of a capability provided to a customer (measure of benefit)	• Fully understand the capability needed (not solution preferred) • Focus on user requirements that flow from needed capability (e.g., on call deployment)
Interoperability	• The ability of two or more systems to exchange and mutually use information	• Adopt and implement common standards • Establish common requirements with mission partners
Flexibility	• The ease with which one can alter the architecture to include a capability to perform a new or unanticipated requirement without adding a component	• Adopt and implement common standards • Leverage research and technology • Investigate novel concept of operations for current systems
Adaptability	• The ability to add a new capability component to the architecture to perform a new or unanticipated requirement	• Adopt and implement common standards • Leverage research and technology • Look at commercial applications
Agility	• Measure of ability to make required changes to an architecture	• Break down barriers to agility (e.g., processes, authorities, etc.)

Some of the principles and definitions necessary of responsive space and their link to actions. Utility, interoperability, flexibility, adaptability, and agility are just some of the factors that must be considered.

common infrastructure and services. Because of the standard way satellite information is both represented and transported, space and ground situational awareness is enabled across all centers and missions in the enterprise.

Common Command and Control Services

A look at a typical satellite operations cycle in the satellite operations center at Schriever Air Force Base illustrates the potential advantages of a command and control framework with a standard communications infrastructure and services. The satellite operations centers generate requests for AFSCN antenna services to mission planning personnel at Schriever Air Force Base generally two weeks before the required satellite contacts. The mission planning personnel perform the orbit management and mission scheduling function. To support this process, a cycle of information is needed to feed the orbit management, mission scheduling, and real-time satellite contact execution process. One portion of this information cycle is illustrated in the following steps:

1. Each day during satellite contacts, AFSCN tracking stations produce tracking data that is delivered to the satellite operations center. The telemetry and commanding software systems in the operations center receive the data and pass them to the orbit management systems in each operations center.
2. Operations personnel responsible for orbit management periodically determine satellite ephemeris from tracking data collected over several satellite contacts to predict when the tracking stations will be able to view the satellites two weeks into the future. From this prediction, calculated antenna look angles are also created for future AFSCN service opportunities.
3. Operations personnel responsible for mission scheduling employ satellite visibility information as well as other resource information to assign specific satellite supports to remote tracking stations in the future. The results are reviewed by the satellite operators and reconciled against an established priority scheme to generate an overall schedule for satellite supports. The resulting schedule is sent to the satellite operation centers and the assigned remote tracking stations. Specific contact support plans and operational crew assignments are developed.

In a compatible command and control framework, the same satellite tracking information going from the AFSCN to the satellite operation center's standard communications infrastructure would be published by the infrastructure using a standard message format. The information would be subscribed to by an orbit management service that also publishes its information to the bus. A mission scheduling service could subscribe to that information to create its candidate resource requests and coordinate the schedule with the AFSCN planning and scheduling organization, which is also connected to the satellite operations center communications infrastructure to adjudicate contention of resources. Once the AFSCN allocates resources, the mission scheduling service publishes the contact schedules and associated instructions to be passed to the operational crews that will execute the satellite contacts on shift. As shared orbit management and mission scheduling services become more efficient and automated, the number of operations personnel can be reduced.

The power of using a standard communications infrastructure and shared services becomes clearer as other satellite systems are added. The next satellite mission will need only to publish its information—in this case, satellite-tracking information—using the same message and data standards. It does not need to develop its own services.

Enabling Situational Awareness

Another advantage of the command and control framework is that all satellite applications have access to the same information traveling through the infrastructure. This enables situational awareness of operations in real time. Publishing data across all satellite operations centers and satellite programs on the standard communications infrastructure augments development of value-added applications that are not easily created in today's stovepipe environment.

As an example, telemetry made available in a standard form from all satellites can be used to build applications that identify the effects of space weather across the entire space environment. For national security, other applications could provide national leaders with indications of space attacks and assessments of national space mission status in real time during times of conflict.

Other value-added capabilities that can emerge from a compatible command and control framework include adding greater opportunities for automation of satellite operations to reduce costs and adding high-level enterprise management to the nation's space ground infrastructure.

> *Another advantage of a compatible command and control framework is accessibility to information exposed by applications across the enterprise. This enables situational awareness of operations in real time.*

SMC Concept Explorations

To explore the technical feasibility and opportunities of moving to a compatible command and control framework, SMC's Satellite Control and Network Systems Group initiated a concept exploration study and testbed development effort using the Aerospace Ground Systems Laboratory, starting in mid 2008. The objective was to look at potential options for a middle-of-the-road approach between the extreme commonality of the Data Systems Modernization and the extreme specificity of stovepipe systems. The laboratory started with the NASA Goddard Space Flight Center's command and control framework, called Goddard Mission Services Evolution Center (GMSEC). The GMSEC implements many of the features of a compatible framework for Goddard satellite missions and proved to be a valuable starting point for SMC's exploration of framework concepts. A key factor in the selection of the Goddard framework was its independence as a government agency from the influence of vendor-proprietary solutions.

Aerospace Ground Systems Laboratory Testbed

The testbed created by the Ground Systems Laboratory implements the framework structure of a standard communications infrastructure using either the GMSEC bus or a commercial sockets-based bus product (such as the TIBCO Software bus) and the NASA-developed application programming interface. The programming interface was instrumental in allowing command and control components to rapidly integrate the bus and messaging standard with the framework in a manner resembling a "plug-and-play" capability.

Four satellite telemetry, tracking, and command systems were rapidly integrated using adaptors developed by vendors and the Ground Systems Laboratory. In fact, three of the four applications were successfully integrated within the first two months of building the testbed and demonstrated passing telemetry across the bus.

These systems used simulated data for both NASA and Air Force satellite missions. Satellite command and telemetry data were simulated using a commercial off-the-shelf (COTS) simulator—SAGES (Satellite and Ground Environment Simulation)—used in training Air Force satellite operators for both the Global Positioning System (GPS) and Defense Satellite Communications System (DSCS)-3. The systems included simulated data from AFSCN tracking stations.

For added realism, actual front-end hardware commonly used at the satellite operations centers and AFSCN was also integrated in the testbed, enabling researchers to begin exploring options for the framework to monitor and control network hardware. NASA provided various tools—for example, a system monitor tool called GREAT (GMSEC Reusable Events Analysis Toolkit)—to help manage the framework, monitor traffic on the bus, and display SMC satellite data in messages.

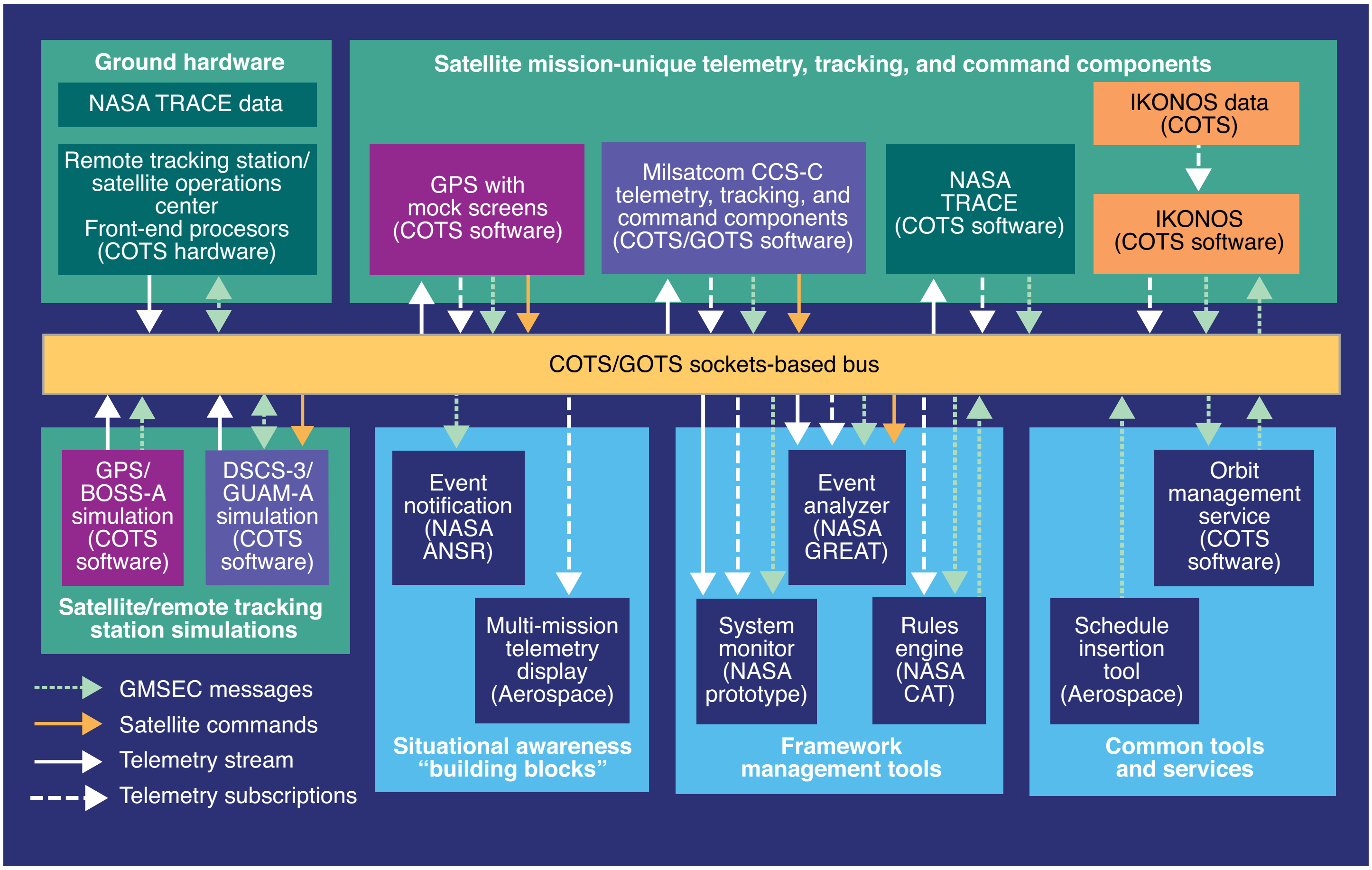
The Ground Systems Laboratory also developed a multimission telemetry display to show the sharing of information across satellite missions that would be needed to support space situational awareness. In addition, sample services were created, including one that used a COTS orbit analysis product to help simulate orbit management. This service subscribed to simulated tracking data for both GPS and DSCS-3 satellites using AFSCN remote tracking stations in Guam and Boston and published predicted satellite ephemeris and real-time visibility information.

Phase One Study Findings

With the completion in February 2009 of phase one of the study by the Ground Systems Laboratory, the testbed successfully showed features and potential problems of a compatible command and control framework in operation with Air Force mission data. The following list includes some of the specific activities accomplished using this testbed.

- Demonstrated a shared communications infrastructure based on commercial publish and subscribe technologies with standard interfaces supporting telemetry streams and telemetry mnemonic subscriptions from six different satellites.
- Simulated multiple telemetry sources on a common message bus, subscribed to by current telemetry, tracking, and command applications used by the Air Force, such as Milsatcom CCS-C (Command and Control System–Consolidated) and GPS AEP (Architecture Evolution Plan).
- Controlled the operation and configuration of AFSCN front-end hardware using NASA GMSEC standard messaging.
- Demonstrated a rudimentary situational awareness capability by merging telemetry information from both DSCS-3 and GPS satellites in a common display.
- Measured the performance of adding the GMSEC application programming interface and a middleware sockets bus to real-time commanding, which showed minimal impact to real-time operations.
- Executed a simulated DSCS-3 satellite state-of-health and battery reconditioning support using the NASA command and control framework, including message bus and standard messages.
- Demonstrated the feasibility of using shared services for orbit management and mission scheduling between two satellite missions, which now duplicate this functionality in their own stovepipe implementation.
- Proved the plug-and-play capability of framework components and the infrastructure's middleware by replacing the GMSEC bus with a commercial bus.
- Illustrated the need for security features in the GMSEC implementation to meet DOD requirements.

In addition to using the testbed to assess command and control framework concepts, Aerospace also performed detailed analysis of the GMSEC standards and application programming interface implementation to assess overall maturity and identify gaps in capabilities needed by an SMC framework. The maturity analysis had three separate components—an automated code analysis, a detailed code walk-through, and an



The command and control framework testbed, created by the Ground Systems Laboratory, implements the framework structure of a standard communication infrastructure using either the GMSEC bus or a commercial sockets-based bus product (such as the TIBCO Software bus) and the NASA-developed application programming interface. The interface was instrumental in allowing command and control components to rapidly integrate for "plug-and-play."

industry questionnaire. The code analysis provided several useful metrics, including code complexity, code/comment counts and ratios, and object-oriented metrics. The detailed walk-through of the C++ source code focused on industry standard best practices, programming conventions, style, and functionality. The user survey was sent to industry partners with current experience not only with the GMSEC application programming interface, but also with relevant satellite command, control, communications, and telemetry programs.

The application programming interface was found to be flexible and usable with sufficient functionality. Overall, the complexity metrics indicated a relatively low-risk, maintainable framework; however, detailed analysis of the framework revealed several areas needing improvement—specifically in security, logging, and complexity of certain high-use software components.

Aerospace Conclusions

Based on the results of phase one of the study, Aerospace concluded that a compatible command and control framework or architecture is technically viable for Air Force satellite operations centers. A key finding was the lack of adequate data standards for satellite command and control information to complete a comprehensive framework definition. Without this standard, integration of new satellite missions into the framework would be more costly and less rapid.

Aerospace recommended that the government take a lead role in defining these command and control standards. Industry efforts to create a data standard through the Consultative Committee for Space Data Systems—particularly, the XML Telemetric and Command Exchange—are a good source for the government to derive a suitable data standard that could be implemented by vendors economically.

The Aerospace Ground Systems Laboratory is expanding the use of the testbed in phase two of the study to look into specific issues important to the Air Force, such as security and unique AFSCN interfaces. In particular, information assurance features will be defined for the framework and their impacts on performance will be assessed on the testbed.

Acknowledgments

Many individuals, organizations, and companies helped create the testbed and results provided in this article. Col. Philip Simonsen and Maj. Matthew McQuinn of SMC's Satellite Control and Network Systems Group provided funding support. Lamont Williams of Aerospace was instrumental in providing guidance during the study. Dan Smith and his GMSEC team at NASA Goddard provided expertise and software that jump-started the testbed. Integral Systems Inc., L3 Communications, Lockheed Martin, Harris Corporation, TIBCO Software Inc., and a.i. solutions loaned software and hardware and provided free technical support. Finally, thanks goes to members of the Ground Systems Laboratory team that built and analyzed the testbed including Prashant Doshi, Andrew Gilbertson, Cathy Proplisch, Alex Martinello, Eric Nelson, Thomas Eden, and Sky Troyer.

Developing a Responsive Ground System Enterprise

Responsive space requires responsive ground systems. Aerospace is helping to establish a comprehensive ground system enterprise that can meet the anticipated tactical demands.

Rico Espindola and Gayla Walden

The Operationally Responsive Space (ORS) Office was established by Congress in May 2007 to spearhead development of capabilities that would enable the timely and assured application of space power to support theater operations on the ground. Some of these capabilities would derive from the redirection of current systems, and some from the development of new systems to augment and replenish capabilities.

ORS is designed to enable military planners to respond to unexpected loss or degradation of existing capabilities and provide timely availability of new or expanded capabilities. The goal is to bring new assets on line in a matter of months (Tier 3), weeks (Tier 2), and hours (Tier 1). One key element of the ORS concept is a responsive ground system enterprise that can accommodate rapid developments in the space and user segments. Individual military services and organizations have been developing their own service-oriented architectures for satellite command and control, and ORS requires a ground system enterprise that can link these disparate systems. Within the ORS Office and partner organizations, Aerospace is supporting activities to establish a compatible architectural framework for satellite operations.

ORS Initiatives

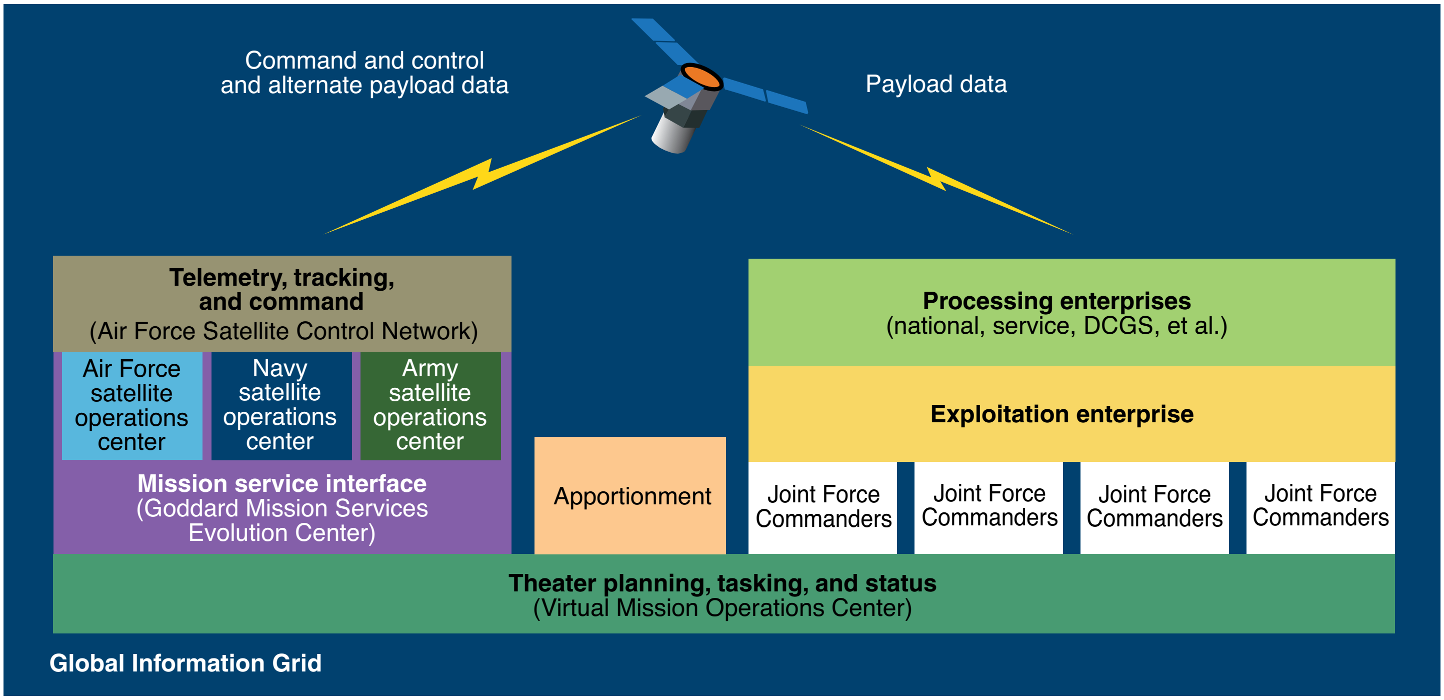
The ORS ground system enterprise envisioned for 2015 will support augmentation, reconstitution, and operational demonstrations. The architecture was baselined to support intelligence, surveillance, and reconnaissance (ISR) missions. It will provide a Web-based small-satellite planning and tasking tool for joint force commanders that accesses a virtual ground station to provide all command and control and tasking for ORS systems on orbit. The data collected by an ORS spacecraft will be sent to a ground station using DOD-selected formats, protocols, and interfaces. This accommodates the use of disparate data-processing systems and limits the need for the ORS Office to develop additional user hardware and software. The data will be disseminated through the global information grid. Direct downlink of payload data to the joint force commanders or of processed information to a warfighter in the field is an end-state objective.

Key capabilities for the 2015 timeframe include autonomous operations for multiple constellations of small satellites; synchronization of ORS assets with other available capabilities; payload tasking and request tracking through a simple user interface; standard vehicle maintenance; payload mission planning; standard command and control of the spacecraft through ground-based and space-based relay; collection of telemetry and mission data through ground-based and space-based relay; processing and dissemination of telemetry and mission data to joint force commanders or provision of direct downlink to a warfighter in theater; and rapid transition of spacecraft demonstrations and prototypes to operational use.

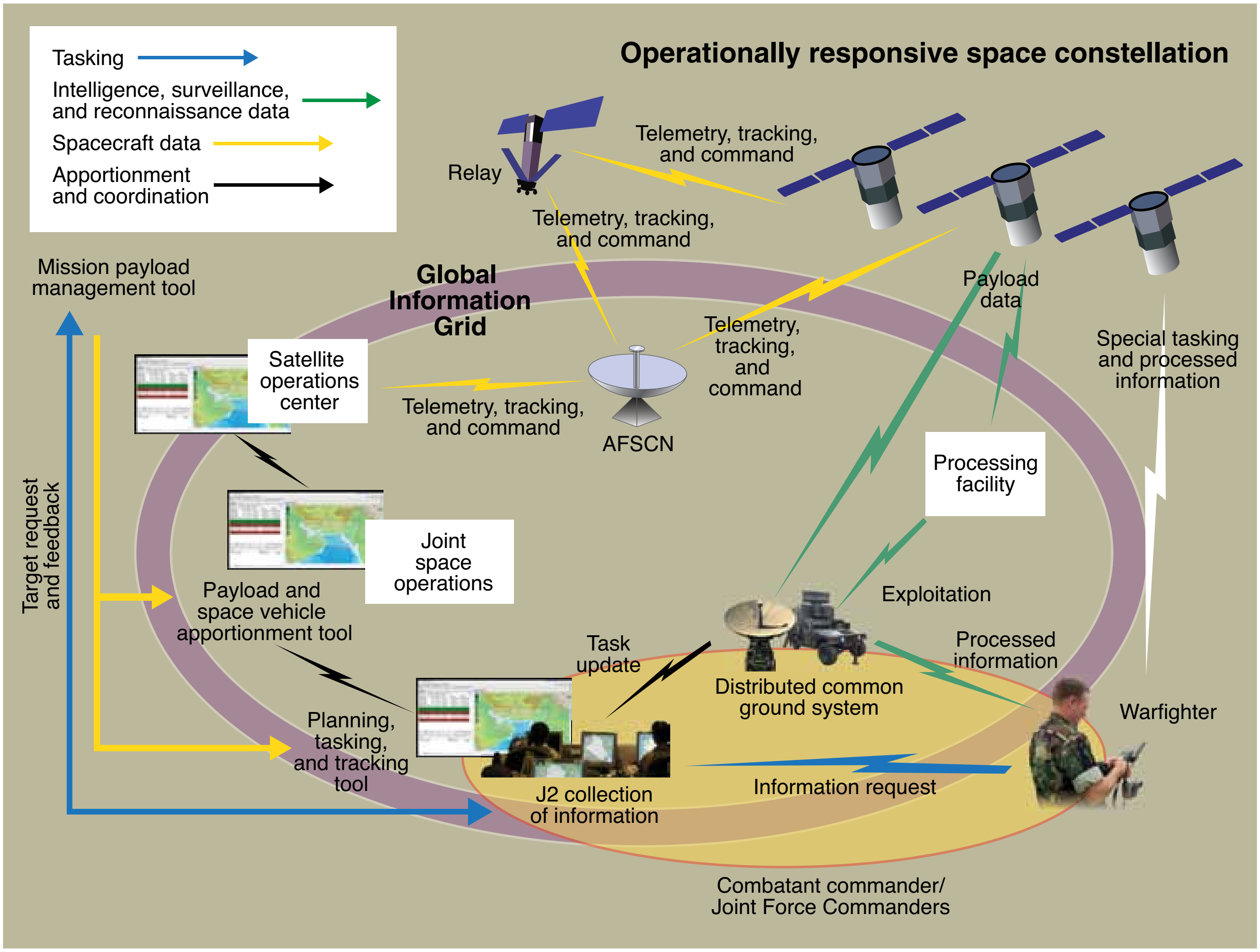
In addition, a number of ancillary needs are being considered. For example, the ground system enterprise should incorporate a modular open-system architecture to promote innovation, standardization, and nonproprietary development. It should connect to exercise and wargame engines and integrate with the global information grid. It should allow autonomous mission planning, data processing, and data distribution and support system-level testing. It should incorporate a responsive information assurance program, a responsive configuration management process, and a responsive frequency management system. It must support, at multiple levels of security, ORS missions involving electro-optical/infrared systems, nonimaging infrared systems, signal intelligence, synthetic aperture radar, space and terrestrial situational awareness, mobile communications, and blue-force tracking. Lastly, it must assign sufficient network priority to ORS missions to expedite the upload of mission tasking and the download of mission data.

Functional Elements

To achieve the envisioned ground system enterprise, the ORS Office has made investments that leverage existing initiatives and architectures. These include Air Force Space Command's Multi-Mission Satellite Operations Center (MMSOC) ground system architecture, NASA's Goddard Mission Services Evolution Center (GMSEC) message bus middleware, the Naval Research Laboratory's Virtual Mission Operations Center (VMOC), and the Distributed Common Ground System enterprise. All of



The operationally responsive space ground systems enterprise service layer. The setup features military satellite operations centers that can share information.



The operationally responsive space ground system enterprise for intelligence, surveillance, and reconnaissance. The constellation includes the functions of telemetry, tracking, and command, payload data, and special tasking and processed information. It is networked through the global information grid and AFSCN.

these elements will be brought together for the first major mission of the ORS Office, the ORS-1 satellite.

MMSOC Ground System Architecture

Air Force Space Command is establishing a high-level operational concept for responsive satellite command and control that aligns with the intended transformation of the satellite operations enterprise architecture. Various command and control systems are being assessed as part of this transition. One such system is the MMSOC ground system architecture, developed by the Space and Missile Systems Center (SMC) Space Development and Test Wing. SMC had been directed to replace an aging ground system with a new, open system that could support unique technology demonstration flights and respond to space operational communities using limited personnel while lowering development and sustainment costs and reducing schedule without increasing technical risk. The MMSOC ground system architecture is structured to support this mandate. It provides telemetry, tracking, and control through the use of open-system and COTS components. It accommodates the integration of newly developed command and control systems through an incremental development process.

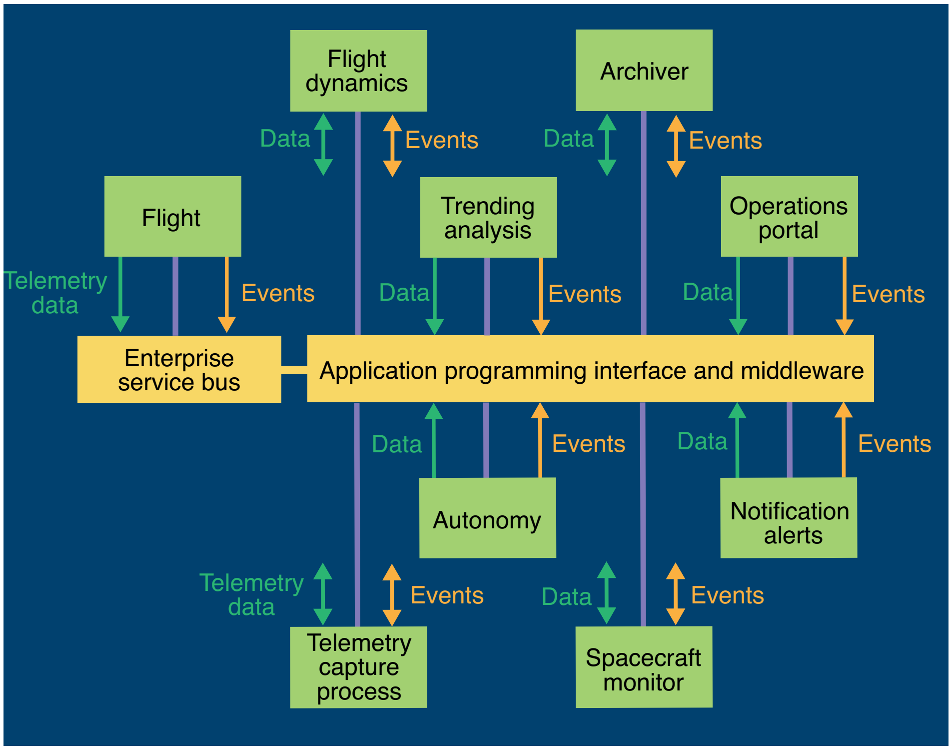
DOD experimental and demonstration satellites are typically one-of-a-kind missions designed to last about a year. The MMSOC ground system architecture supports every aspect of such missions, including planning, training, mission preparation, launch and early orbit operation, normal operation, data collection and dissemination, and vehicle health and safety monitoring. Some missions end the experimental phase with a residual operational capability. The MMSOC ground system architecture also supports this residual activity through a collaborative environment that facilitates the efficient transfer of capability from the research arena to the operational theater. This collaborative environment, in which both the transferring and receiving organization trade and share support responsibilities, makes it easier to organize the personnel, processes, and resources necessary to develop and field one-of-a-kind missions. Moreover, the commonality inherent in the use of open systems generates efficiencies in both training and maintenance, minimizing funding requirements in these areas. Likewise, transition of missions and remote backup of operations between similar satellite operations centers becomes more straightforward.

Meeting the challenge of flexible operations at reduced cost requires more than just a materiel solution; process and business rules must also be addressed. The Responsive Satellite Command and Control Division of the SMC Space Development and Test Wing, in conjunction with its contractor team, has developed a strategy for implementing a published future architecture. The strategy employs an evolutionary model guided by an open-systems management plan with interfaces controlled by the architecture services catalog and external interface control document. The open-systems management plan, which Aerospace helped develop, was based on fundamental open-system principles: establish business and technical enabling environments; employ modular concepts; employ business and technical patterns; designate key interfaces; and use open standards for key interface certification and conformance. These principles, combined with the identification of standards (particularly for data and interface control) and the established catalog of services, will allow the program to work with a range of potential missions, reducing unique mission support requirements.

The implementation strategy breaks with the traditional acquisition paradigm in which an extended period of time elapses between the definition of requirements and the fielding of the required capability. Once proven, the MMSOC ground system architecture will be deployed into operational and support components and undergo operational acceptance testing. Operator evaluations will provide feedback for developers and lead to continual system improvements.

The MMSOC ground system architecture is not a "point" solution; continuous upgrades will be necessary to enhance cost effectiveness, ensure sustainability, and prevent system obsolescence. Aerospace helped develop a system evolution plan that will account for both technical needs and projected resources and gradually optimize the system to meet designated targets while maintaining system availability. Part of this evolution plan entails a new block upgrade each year.

The MMSOC ground system architecture has been designated as the primary satellite command and control capability for Air Force missions within the ORS Office. The Block I architecture will be used to support STPSat-2 in early 2010. It will also be installed at one of the satellite operations centers (SOC-11) at Schriever Air Force Base in Colorado Springs to support ORS-1. The Block II study phase was initiated in early 2009, in keeping with the plan for yearly block upgrades. Aerospace is also supporting the Block II study.



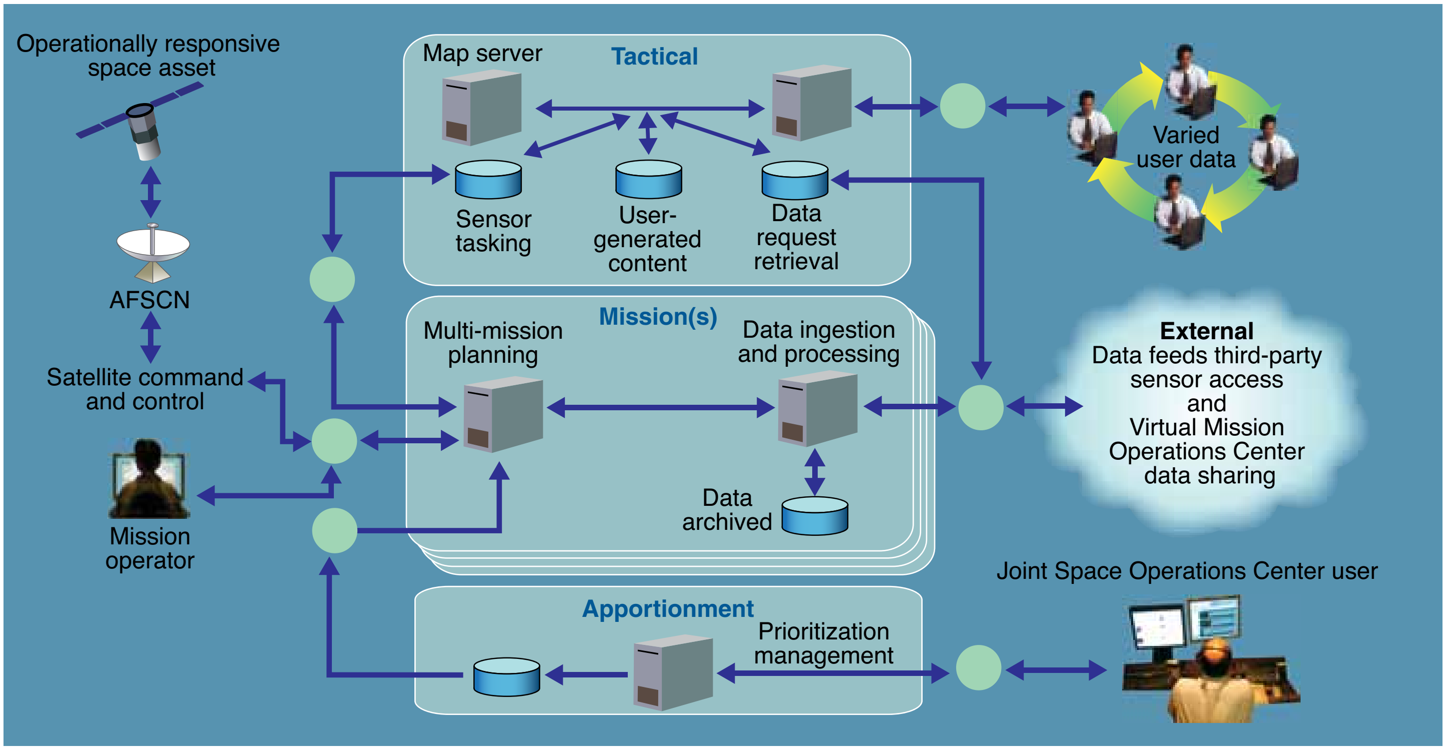
NASA's GMSEC framework is composed of three elements that standardize interfaces, provide a middleware infrastructure, and allow users to choose components for specific missions through an application programming interface. The ORS Office is exploring this effort as it attempts to link disparate command and control centers.

GMSEC

Similar to the Air Force Space Command satellite operations initiative, NASA Goddard Space Flight Center has completed its own transformation and has established the GMSEC framework composed of three elements that standardize interfaces, provide a middleware infrastructure, and allow users to choose components for their specific missions through an application programming interface (API). The GMSEC ground system architecture has supported eight orbiting satellites and is being applied to several of NASA's future missions. Because the ORS Office supports all military services and various organizations, the challenge is to link disparate command and control centers while affording a common architecture across the broader enterprise. The GMSEC message-bus middleware would allow a standard communications infrastructure for compatible command and control interfaces, messaging, and data formats. This could serve as the common mission service interface across the disparate satellite operations centers to enable continuity of satellite operations between systems and communitywide ground situational awareness and space protection.

A common theme at the 2009 Ground System Architecture Workshop (GSAW) cosponsored by Aerospace was command and control across various government organizations. For example, SMC presented the MMSOC ground system architecture. NASA presented a concept for enabling rapid system configurations. The ORS Office presented the 2015 ground system enterprise. A session jointly hosted by NASA and the National Reconnaissance Office discussed the use of common command and control standards across government and industry. It quickly became apparent that all these organizations were independently working toward a common command and control framework, and their efforts would be multiplied through greater collaboration. Accordingly, these organizations formed a committee (known as the Joint SatOps Compatibility Committee, or JSCC) to help steer their efforts toward a compatible space enterprise. Aerospace has been collaborating regularly with members of the committee and continues to explore a compatible command and control framework for SMC.

For example, Aerospace recently completed the first phase of a compatible architecture study that used NASA's GMSEC framework with current command and control software and hardware. As part of this study, a flexible ground system framework was demonstrated in a laboratory testbed in the Aerospace Ground Systems Laboratory. The effort showed the viability of a compatible framework and identified



The Virtual Mission Operations Center (VMOC) architecture, which is managed by the Naval Research Laboratory. The ORS Office has selected the VMOC as the tasking and sensor visualization tool for its 2015 ground system enterprise. Aerospace is helping to define the objectives necessary to make this vision a reality.

shortcomings in data standards that would need to be addressed before such a system could be optimally implemented. The ORS Office and the compatibility committee are adapting the testbed for future missions and initiatives. (For more on the architecture testbed, see "A Flexible Satellite Command and Control Framework" in this issue of *Crosslink*.)

VMOC

The Virtual Mission Operations Center (VMOC) concept began in 2000 with a collaboration between NASA Glenn Research Center and a contracting partner. Between 2004 and 2007, the VMOC focus was on demonstrations supporting the standardization of spacecraft-to-ground interfaces needed to reduce cost, maximize user benefits, and allow the generation of the new procedures required to shape responsive space employment. In 2008, the efforts merged under the Naval Research Laboratory to focus on the integration of all the elements into a system of systems that could begin addressing the needs of responsive space tasking and data collection and processing. The ORS Office has selected the VMOC as the tasking and sensor visualization tool for its 2015 ground system enterprise, and Aerospace is helping define objectives for the VMOC that would help achieve this vision.

The near-term focus for the VMOC is on supporting the TacSat-4 and ORS-1 satellites. TacSat-4 is part of a series of experiments developed by the Naval Research Laboratory in support of ORS objectives. The payloads include mobile communications, blue-force tracking, and data exfiltration. For TacSat-4, the VMOC will interface with the Naval Research Laboratory's Blossom Point ground station and take advantage of that facility's highly automated mode of operations. The interface between the VMOC and the spacecraft operations center is being refined and tested for TacSat-4 and will provide the baseline for ORS-1, which will require the VMOC to interface with the MMSOC ground system architecture at Schriever Air Force Base.

To maximize the benefit on theater operations, ORS assets will need to be directly tasked, just like any other operational asset. VMOC is building a common planning, tasking, and tracking interface that will be integrated with tasking tools such as PRISM (Planning tool for Resource Integration Synchronization and Management). The automated interface between the tactical, apportionment, and mission components of the VMOC will allow scalable multimission planning with a "Fed-Ex" style capability that will allow users to track the status of their data requests.

Using the tactical component of the VMOC as the tasking and sensor visualization tool in exercises and operations will greatly assist in the refinement of organizational roles and responsibilities. It will also provide insight into ORS availability and limitations, allowing operators to evaluate emerging requirements and apply the correct asset at the right time—without putting the platform at risk of being overtasked. The apportionment VMOC component provides the tools needed by the joint force commanders to model and effectively apportion space platforms and sensors for maximum effect. An integrated apportionment allows for rapid changes in the rules that the mission component uses to schedule tasks. By integrating the mission component of the VMOC with the satellite operations centers, the joint force commanders will have direct access to payload scheduling and near-real-time payload tasking using traditional command and control as well as over-the-horizon relay.

Common Data Link and Distributed Common Ground System

For more than a decade, the Common Data Link program has been the DOD standard for assured wideband communications of

The ORS Office conducts rapid assembly, integration, and test demonstrations using AFRL's plug-and-play spacecraft as pathfinding activities for the Rapid Response Space Works. The focus is on the space segment as well as the ground segment components end-to-end to achieve the ORS end-state vision. Here, the ground segment team is employing the flight and ground software for operations as the technicians build the spacecraft within "Chile Works."

tactical intelligence data. Through technology insertion, this family of common hardware and software modules continues to serve on various airborne ISR platforms. These airborne assets are supported by an extensive distributed ground infrastructure for imagery-based intelligence exploitation known as the Distributed Common Ground System.

The Distributed Common Ground System processes U.S. and allied sensor data. It has been optimized for the Joint Task Force and is supporting operations in the Middle East. It is capable of posting intelligence reports within the ISR enterprise and is evolving to a net-centric capability.

Although the Common Data Link is employed on all airborne ISR platforms, it is not employed on space-based ISR platforms to enable tactical operations. Analysis of recent combat operations has identified a need to reduce the latency and increase the persistence of ISR data from space-based systems. The addition of the Common Data Link to military and commercial remote sensing platforms would enable real-time in-theater tasking, collaboration, collection, and dissemination by the warfighter using the existing ground infrastructure.

The U.S. Army, in partnership with the ORS Office, is helping to design, procure, and integrate the technologies and components needed to build a space-qualified Common Data Link payload for military satellites. The ORS Office is supporting design upgrades to miniaturize and space-qualify required Common Data Link components for ORS-1. Aerospace is supporting space qualification using the Berkeley cyclotron. Aerospace is also supporting Common Data Link spectrum analysis for downlink inside and outside the continental United States for ORS-1.

Common Data Link components were tested on TacSat-2 and are flying on TacSat-3, but have not yet flown for an operational mission. Improved link reliability testing of the Common Data Link components on TacSat-2 were not completed before the end of the mission. The Common Data Link is the primary means of downloading payload data from TacSat-3—and based on the first few weeks on orbit, the technology shows great promise in space.

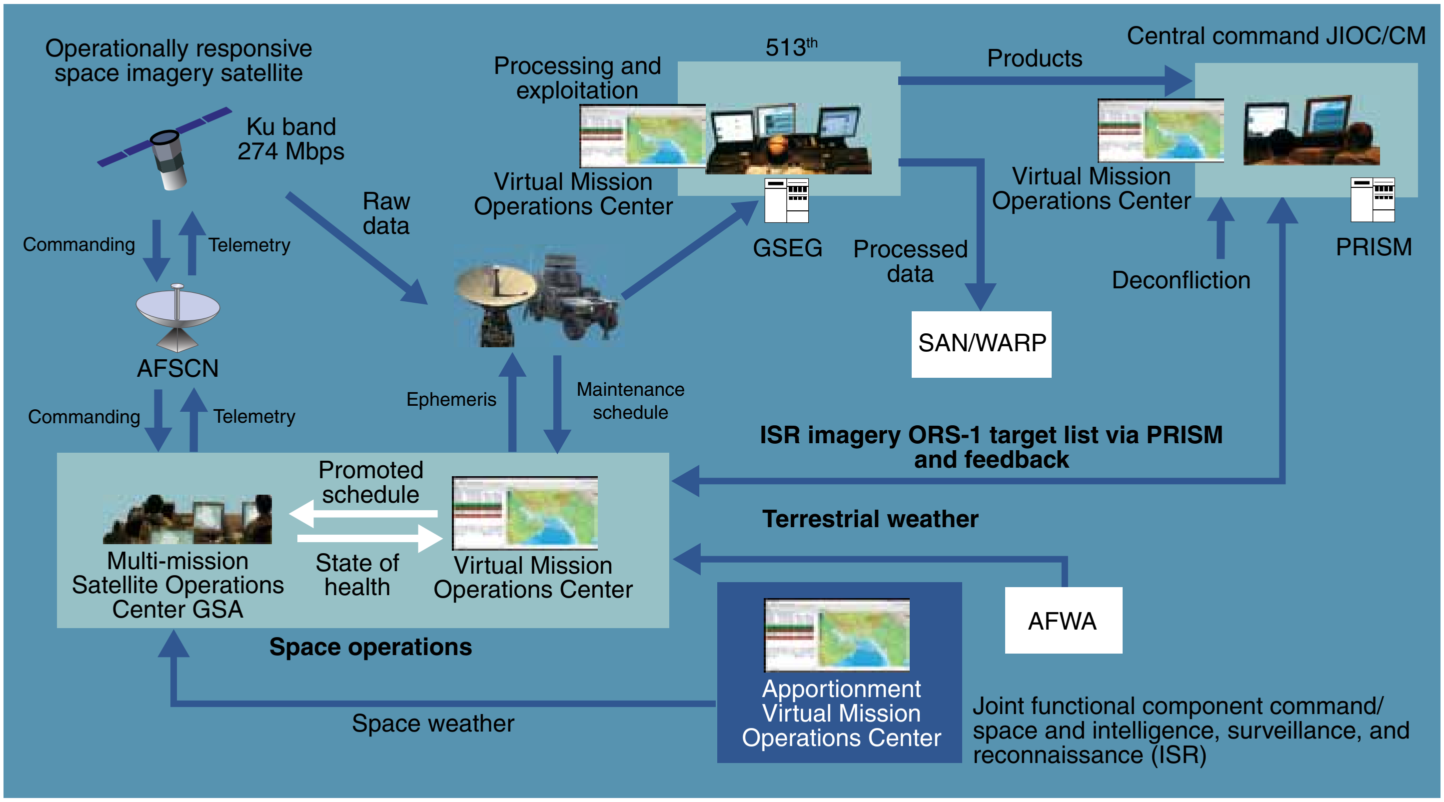
Development Plans

The ORS Office will proceed through three phases—known as the "crawl," "walk," and "run" phases—in developing the envisioned ground system enterprise of 2015. The walk and run phases planned for the 2011–2013 and 2014–2015 timeframes will build upon lessons learned during the 2010 crawl phase and follow-on missions. During this time, the responsive ground system enterprise will also evolve to include other ORS mission areas outside of ISR. As the ORS Office continues to demonstrate responsive space capabilities and creates constellations of ORS assets, the ground system enterprise will have to achieve autonomy and synchronization of all available capabilities. The ORS Office will continue to use the ground system enterprise to refine concepts of operations and procedures for ORS assets and rapidly transition spacecraft demonstrations and prototypes to operational use.

The Crawl Phase

In the 2010 crawl phase, the ORS Office will focus on two primary activities: the ORS-1 satellite and the JumpStart-2 initiative.

Scheduled to launch in 2010, ORS-1 was proposed in response to an operational need for ISR identified by U.S. Central Command and validated by U.S. Strategic Command. ORS-1 will be a "U-2 in space," a tactical electro-optical/infrared surveillance and reconnaissance satellite in a circular, inclined low Earth orbit. SMC's Responsive Space Squadron, part of the Space Development Group, will be executing the ORS-1 mission for the ORS Office under the direction of the DOD executive agent for space. The satellite will be operated by the Air Force under the direction of U.S. Strategic Command. It will make use of the MMSOC ground system architecture



The ORS-1 mission architecture. Scheduled to launch in 2010, ORS-1 will respond to an operational need for an ISR request from U.S. Central Command.

at Schriever Air Force Base and use the VMOC for payload mission planning. It will fly the first version of the space Common Data Link and also use the Distributed Common Ground System enterprise as part of its tasking and data management processes. Aerospace is actively involved in all phases of ORS-1.

JumpStart-2 is focused on equipping the Rapid Response Space Works (a.k.a. Chile Works) at Kirtland Air Force Base to build new spacecraft in response to urgent tactical or strategic needs. The ORS Office envisions a modular approach that would allow plug-and-play integration of "mission kits" consisting of proven bus and payload technologies. Ultimately, these mission kits will allow rapid assembly and integration of space-based solutions stemming from joint force commander needs. These kits will also have to take into consideration the ground aspects of fielding capabilities rapidly. The JumpStart-2 program will work toward the Tier 2 timeline for providing capability on orbit within days to weeks. To achieve this goal, key ground segment enabling capabilities will need to be determined. The ORS Office will take advantage of the GMSEC testbed created in the Aerospace Ground Systems Lab by including key functional elements of the ORS ground system enterprise, the MMSOC ground system architecture, and the VMOC. This ORS proof-of-concept demonstration will also involve building adapters between the GMSEC framework and the Air Force Research Laboratory's PnPSat (Plug-and-Play Satellite) and the Remote Intelligent Monitor System (RIMS) ground system. Additional tasks are underway to build an XML telemetric and command exchange (XTCE) interpreter for the PnPSat RIMS to further enable a compatible space enterprise. The ORS Office is also investigating the possibility of adapting an on-orbit spacecraft within the GMSEC construct. Future tasks will involve other member organizations from the compatibility committee formed after GSAW.

The Walk and Run Phases

During the walk and run phases, the ORS Office will expand the responsive ground system enterprise to include other responsive space mission areas such as communications and space situational awareness and continue to drive to a common ground architecture across the services and space organizations. The ORS Office will continue to apply existing initiatives and infrastructures from the broader DOD and space community and work with its investment partners to achieve the envisioned responsive ground system enterprise by 2015. This can be achieved by understanding warfighter needs, controlling the biggest drivers for innovation lead time, and using open innovation techniques.

Conclusion

The ORS Office recognizes that a responsive space system approach cannot be achieved without a responsive ground segment. Through its expertise in space system architecture and cross-program oversight, Aerospace is helping the ORS Office plan and implement an agile and innovative enterprise that can keep pace with changing technology and evolving user needs.

Acknowledgments

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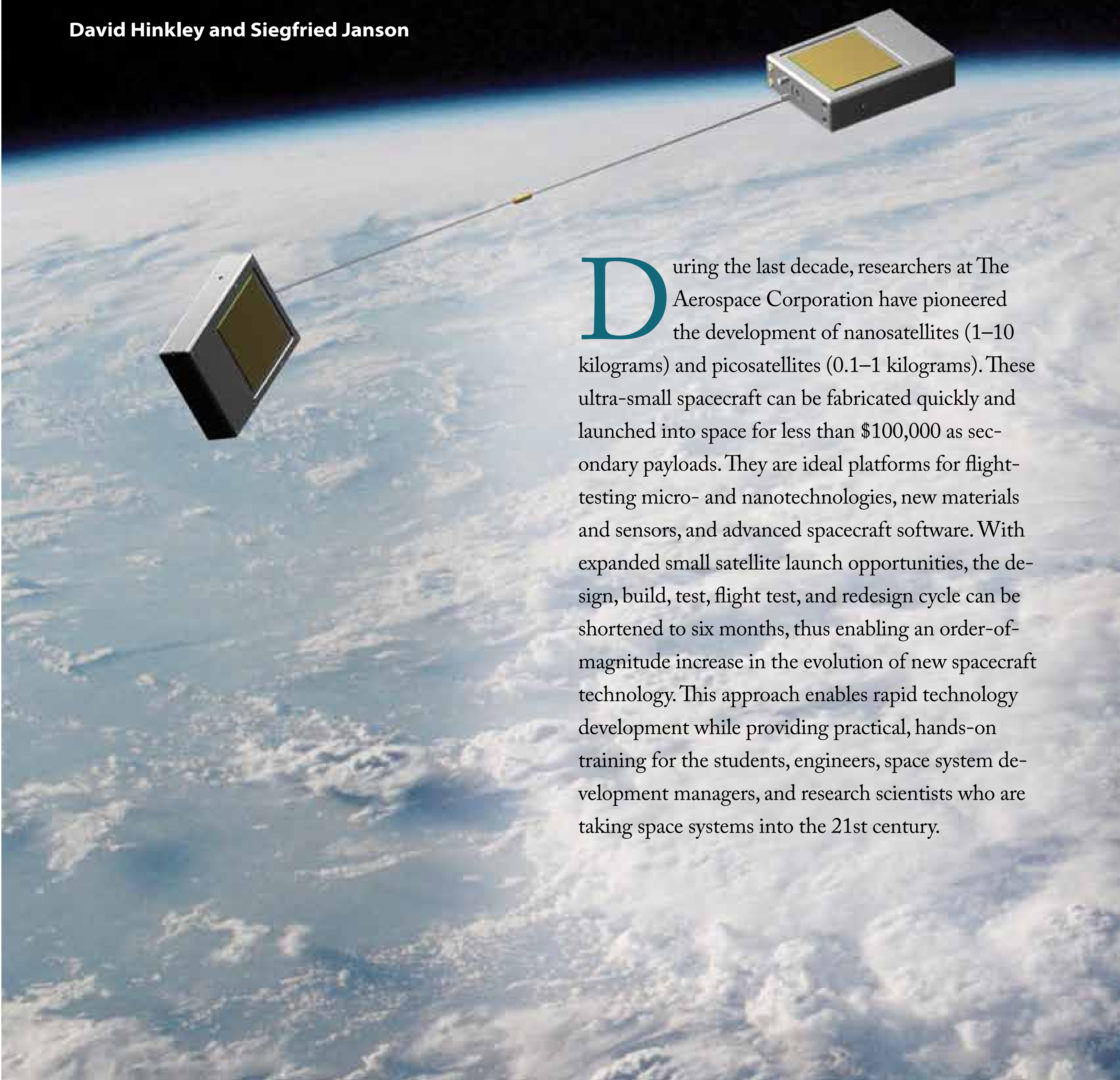
Building Miniature Spacecraft at The Aerospace Corporation

Imagine flying a satellite with a technology freeze date that was only six months ago. Aerospace has completed 11 miniature satellites for technology demonstrations, with an average design, build, assemble, test, and deliver cycle of about a year.

David Hinkley and Siegfried Janson



During the last decade, researchers at The Aerospace Corporation have pioneered the development of nanosatellites (1–10 kilograms) and picosatellites (0.1–1 kilograms). These ultra-small spacecraft can be fabricated quickly and launched into space for less than $100,000 as secondary payloads. They are ideal platforms for flight-testing micro- and nanotechnologies, new materials and sensors, and advanced spacecraft software. With expanded small satellite launch opportunities, the design, build, test, flight test, and redesign cycle can be shortened to six months, thus enabling an order-of-magnitude increase in the evolution of new spacecraft technology. This approach enables rapid technology development while providing practical, hands-on training for the students, engineers, space system development managers, and research scientists who are taking space systems into the 21st century.

PicoSats

The Aerospace program in miniature satellites started in 1999, when a corporate research initiative on microtechnology led to a DARPA (Defense Advanced Research Projects Agency) grant to fly microelectromechanical systems (MEMS) in space. Within six months, Aerospace delivered a pair of 250-gram satellites measuring just 1 × 3 × 4 inches in dimension. Rockwell Science Center in Thousand Oaks, California, provided battlefield radio-node electronics (also funded by DARPA) consisting of a microprocessor and radio. Aerospace packaged, tested, and reprogrammed them as the command and control unit for these ultra-small satellites. This effort brought together corporate engineers from the thermal, mechanical, communications, and software disciplines. These so-called "PicoSats" had basic functionality and minimal mission requirements: survive launch, listen for a ground station, deploy a 100-foot tether (to simulate constellation flight), exercise MEMS radio-frequency (RF) switches, and transmit experiment and housekeeping data. They were released from the 23 kilogram OPAL (Orbiting Picosatellite Automated Launcher) satellite in February 2000.

The two largest concerns for mission success were satellite tracking and the communications link budget. Each satellite could only generate 64 milliwatts of RF power, and the circular orbit was 773 kilometers in altitude. To enhance tracking of the satellites by the Air Force Space Surveillance Network, the tether between them incorporated gold dipole threads to increase the radar cross section. To close the communications link, a huge 150-foot-diameter antenna at SRI International in Menlo Park, California, was required—but its very narrow beamwidth added to the tracking challenge. After ejecting from OPAL, the tethered PicoSats operated for about two and a half days. Tracking was good; data from the MEMS switch experiment and measurements of satellite temperature were downlinked, and new commands were uplinked. It was a successful mission, but with plenty of lessons learned.

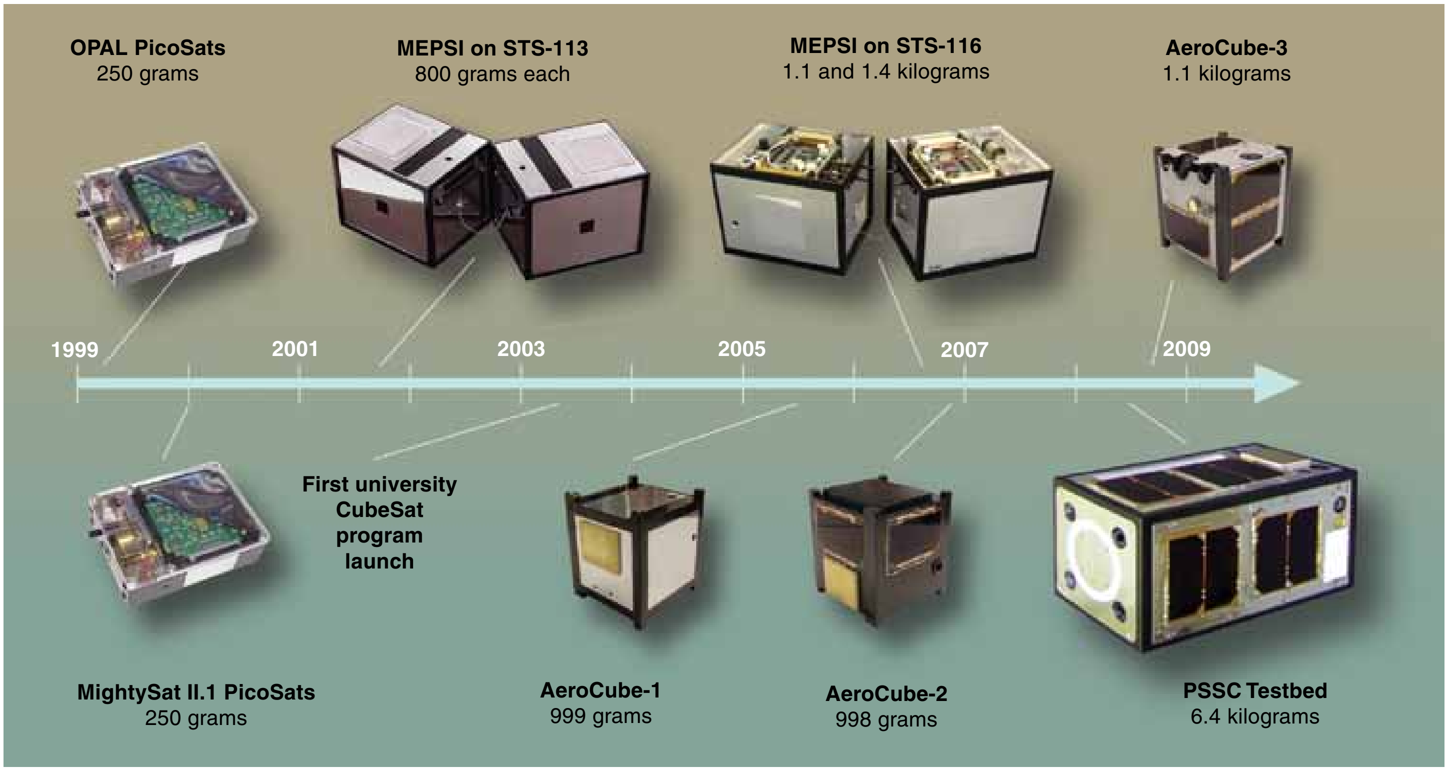
The 250-gram PicoSats (top) and the 150-foot-diameter ground station antenna needed to close the communications link to space (bottom).

An opportunity to eject another pair of tethered PicoSats presented itself several months after the OPAL delivery. A payload on the Air Force Research Laboratory's MightySat II.1 research satellite was demanifested late in the integration cycle, and a single OPAL-like launch tube would fit in the available volume. Aerospace built a copy of the OPAL launch tube and another pair of 1 × 3 × 4 inch PicoSats in six months, delivering in December 1999. The two 250-gram picosatellites would be tethered as before and would repeat the previous constellation exercise. They also would test an improved set of MEMS RF switches for DARPA, demonstrate the feasibility of storing miniature satellites onboard a host vehicle for a long period of time, and provide an exercise in integrating secondary satellites onto a high-value host to illuminate the practical mission assurance concerns.

In September 2001, the MightySat II.1 satellite released the tethered PicoSats after 15 months of storage on orbit. The SRI International ground station contacted both units and downlinked temperature and MEMS-switch resistance data; however, the communications link was worse than in the prior mission, and few contacts were made before the mission was declared over three days later. Nonetheless, the mission demonstrated the feasibility of including a daughtership on a mothership. This paved the way for the second generation of miniature satellites from Aerospace, the MEMS-Enabled PicoSatellite Inspector (MEPSI) series.

MEPSI

The MEPSI spacecraft was designed to test miniature system and subsystem technolo-



Since 1998, Aerospace has built 11 picosatellites and nanosatellites. Eight have been tethered pairs, and three were individual CubeSats. One overriding goal of these efforts has been to demonstrate that miniature satellites, launched as secondary payloads, can do a great deal to mitigate risk on much larger programs.

gies required for kilogram-class satellite inspectors and assistants. The concept included one or more satellite inspectors that would reside on a large host satellite—with minimal impact on mass and volume—to be ejected on command in the event of an on-orbit anomaly. They would photograph the host to provide high-resolution imagery of damaged or undeployed structures, or provide real-time imaging of complicated deployments and proximity operations directly to a ground station.

The MEPSI-class satellites had to be very capable spacecraft to carry out the inspection mission. Several functions—propulsion, closed-loop attitude control, ranging, and a radio downlink with sufficient bandwidth to transmit images to a ground station—were hitherto unheard of in a satellite of this size. Furthermore, the MEPSI had to be extremely reliable because it would orbit a high-value satellite, and a collision was unacceptable. For these reasons, a spiral development plan was chosen, whereby each successive MEPSI would be an improvement on the prior version.

For the first MEPSI mission, two 800-gram picosatellites and a space shuttle-qualified launcher were designed, built, tested, and delivered in two years. The loaded launcher was installed onto the sidewall of the cargo bay of the space shuttle Endeavour one month prior to liftoff of STS-113 in December 2002 (so close to the liftoff date that the orbiter was already in a vertical orientation). The two identical 4 × 4 × 5 inch picosatellites were powered with primary batteries and had a flight computer, radio, triaxial rate sensors, and triaxial accelerometers. They were tied together with a 50-foot tether with gold dipole wires woven along its length to increase the radar cross-section of the pair. The satellites were identical and they had no redundant subsystems, so having two of the same design provided the only redundancy against random defects and workmanship errors. On orbit, once released from the launcher, they turned on and started recording the accelerations and angular rates caused by the unspooling of the tether and the eventual rebounds caused by the end of the tether. The purpose of this exercise was to compare the performance of two different types of MEMS rate sensors installed in each satellite. The Jet Propulsion Laboratory (JPL) was Aerospace's partner on this mission. JPL integrated and characterized the MEMS inertial rate measurement unit on each satellite.

This mission was only a partial success. A new picosatellite launch system for the space shuttle and two new satellites had been designed, qualified, and delivered. The NASA photographs of the picosatellite ejection were exciting and dramatic, and they helped to promote this class of satellite. The Aerospace Corporation ground station team, with assistance from the USAF Space Surveillance Network, successfully tracked the satellites, and beacons were received that contained modest state-of-health data. Unfortunately, two-way communications were never established, and the acceleration and rotation rate mission data were not downloaded from either satellite because of a systematic problem with the satellite radio receivers. The error was known prior to delivery, but there was insufficient time to fix it (*Rule 1: Primaries do not wait for secondaries!*). The failure of this particular mission objective resulted in a mission assurance study in which the architecture of the satellite bus was found to have limited the designers' ability to react quickly and fix the problem in time. The picosatellite team redesigned the satellite bus to be more flexible and easy to debug.

The second MEPSI attempt had to wait for STS-116 in December 2006, mainly because of the orbiter disaster in 2003. It used the new bus architecture and new subsystems. Once again, a tethered pair of picosatellites was ejected from the space shuttle; this time, however, the dipole-laden tether was only 15 feet long to keep the two satellites in visual distance. The goal was to practice a visual inspection mission: one unit was configured as an "inspector," and the other was the "target." The two satellites were functionally identical except that the inspector had maneuverability. It used a five-thruster propulsion unit (invented and patented at The Aerospace Corporation) and three orthogonal reaction wheels to maneuver so that two tiny color 640 × 480 pixel resolution (VGA) cameras could take pictures of the target. The target had no attitude control, but had a suite of five color VGA cameras on different faces to take pictures of the inspector. Neither satellite had sensors for detecting the other—those subsystems were not ready in time. Therefore, all camera operations and attitude control changes had to be commanded while they were in contact with the ground station. Both satellites, as in all prior missions, could be commanded from the ground station independently.

The 1.4-kilogram inspector and 1.1-kilogram target were ejected from the space shuttle Discovery on the STS-116 mission in December 2006. Immediately upon release, they began preprogrammed operations that included taking photographs of the shuttle and recording satellite rotation rates and accelerations during tether deployment and subsequent rebounds. Tracking and ground operations were nominal, and the communications link was strong. The reaction wheels and cold-gas thrusters were successfully tested, but no pictures of the other picosatellite were successfully taken because, in sunlight, the tether between them was so bright, it overexposed the images. Nominal mission life was two weeks because the satellites used primary batteries, but the mission was actually shorter because of a memory overflow condition. (Both satellites suffered the same fate, which suggested a systematic error.) Nonetheless, the STS-116 picosatellites were a large step forward in demonstrating the capabilities required by a MEPSI vehicle.

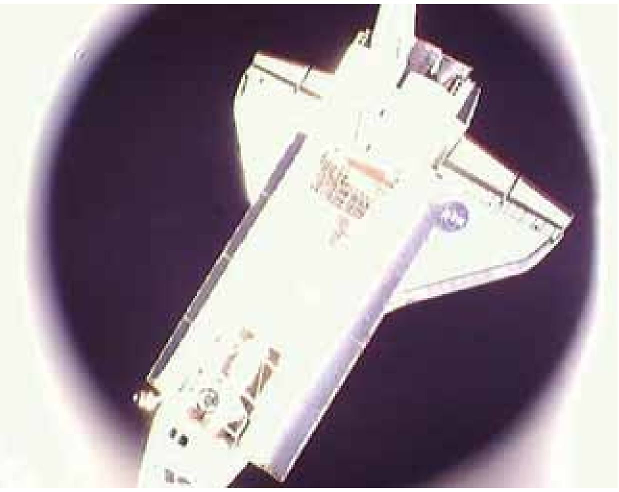
CubeSats

At the same time that Aerospace was building the first MEPSI pair for STS-113 and the space shuttle picosatellite launcher, Stanford University was teaming with California Polytechnic State University (Cal Poly) to define a new standard of picosatellite called a CubeSat along with a deployment system that was compatible with expendable launch vehicles. In 2000, they jointly introduced the new specification: a cube-shaped satellite that was 10 centimeters on a side and weighed at most 1 kilogram. The interface control document was simply a single 11 × 17 inch drawing that defined the mechanical attributes of the standard. These terse requirements—along with an advertised integration and launch cost of $40,000 per CubeSat—resulted in a frenzy of development at universities around the world. In 2003, the first CubeSat launch placed six of these miniature satellites into a sun-synchronous orbit from a Russian launch vehicle. Other CubeSat cluster launches occurred in 2005 (3 satellites), 2006 (15 satellites), 2007 (7 satellites), and 2008 (6 satellites). All of these used a foreign launch vehicle except for one CubeSat in 2006 (NASA's GeneSat).

The Aerospace Corporation picosatellite group began participating in this CubeSat community in 2004. At that time, the return-to-flight status of the space shuttle was still unknown, and it was important to routinely fly satellites to keep program office customers interested and to keep the picosatellite development team engaged. The team reserved a spot on the next Russian Dnepr flight and set to the task of developing AeroCube-1, its first CubeSat. The goal was to test MEPSI hardware and buy down risk; AeroCube-1 was a repacking of the MEPSI electronics. The two form factors were not too different: a CubeSat at 10 × 10 × 10 centimeters had a little less volume than a 4 × 4 × 5 inch MEPSI picosatellite. AeroCube-1 therefore featured the improvements and new capabilities of the MEPSI picosatellites on STS-116 except for propulsion and reaction wheels. Unfortunately, the AeroCube-1 satellite waited at the integrator for 15 months until the primary satellite was ready (*Rule 2: Primaries can hold up secondaries!*). To add insult to injury, the Dnepr vehicle failed and crashed back into Earth. However, the exercise of building the CubeSat proved beneficial when the time came to build the MEPSI flight articles a year later. The process had revealed important assembly issues, fostered the development of proper test procedures, and kept the team both together and in practice.

AeroCube-2 was an improvement over AeroCube-1 with better packaging and new capabilities. The new subsystems included the first rechargeable power system and a deorbit balloon. Four solar cells, one on each of four faces of the CubeSat would recharge the satellite's lithium ion batteries. The deorbit balloon was a 9 × 6 inch pillow-shaped Kapton bag that was inflated by a gas stored onboard in a system derived from the MEPSI mission thrusters. AeroCube-2 reached orbit in April 2007, but the rechargeable power system was not up to the task and it operated for less than a day. During that time, however, ground stations downloaded pictures and state-of-health data. Included was a picture of the Cal Poly CubeSat CP-4, the first and only picture taken of one CubeSat by another in space.

In 2008, Aerospace developed its third and most sophisticated CubeSat, AeroCube-3. It featured new technology including a 200-foot long tether, a tether cutter, a tether reel, a 30-inch nearly spherical deorbit balloon, a sun sensor, an Earth sensor and two new customer proprietary sensors. It also had a new rechargeable power system very conservatively sized. It was launched on a Minotaur launch vehicle


Photograph of the space shuttle Discovery taken seconds after ejection by a MEPSI spacecraft.


A picture of the Cal Poly CubeSat CP-4 taken by AeroCube-2—the first and, so far, only instance of one CubeSat photographing another.

with TacSat-3 as the primary payload in May 2009. The tether was intended to keep AeroCube-3 within camera distance to the upper stage. In the first part of the mission, it would take pictures of the upper stage in a MEPSI-like fashion. The tether reel would close the distance as needed and the tether cutter would free the researchers to perform the second part of the mission. In the second phase, a permanent magnet passively orients the free-flying spacecraft, creating North and South faces. A single miniature reaction wheel spins the spacecraft on an axis normal to the North and South faces. Two proprietary sensors and a color VGA camera sweep the surface of Earth at a rate determined by the reaction wheel, gathering data and snapping pictures. AeroCube-3 continues to be operational and 28 MB of data have been downlinked (1000 pictures and satellite health telemetry).


PSSC Testbed picture of the California coast, roughly from San Diego to Malibu.

PSSC Tested

The first Aerospace nanosatellite, the Pico-Satellite Solar Cell (PSSC) Testbed, was launched in November 2008 from the space shuttle. Measuring 5 × 5 × 10 inches in dimension, the satellite's primary mission was to test two new types of solar cells in the harsh space environment. It was designed to serve as a pathfinder for a second satellite that will fly in geosynchronous transfer orbit to obtain accelerated space environment degradation data for advanced solar cells. The resulting data will provide insight into the actual performance of new solar cells before they are used to power a multimillion-dollar national security spacecraft. In the past, space missions have been adversely affected by the degradation of solar cells, and attempts to collect actual exposure data for new cells have been delayed by several years due to the time required to build and launch conventional experiments. The PSSC Testbed solves that problem.

The PSSC Testbed bus includes a solar power system that can characterize new solar cells. Once it has been successfully demonstrated in space, it can be used as a standard testbed for any type of future solar cells with minimal modification. Ultimately, with a picosatellite launch capability on multiple EELV missions, a PSSC Testbed could be launched on demand, thus further reducing the time between initial production of new solar cell technology and the receipt of orbital performance data.

In addition to performing its primary mission, the pathfinder PSSC Testbed has been photographing Earth for more than 90 days. Operators have already downlinked more than 500 images and 18 megabytes of data.

Rapid Development

As these projects illustrate, speed and cost are two of the primary advantages of using small satellites for technology development. It typically takes about five STE (staff years of technical effort) to design and build an Aerospace picosatellite. In addition, purchased materials and parts reach about $100,000 when developing a new design. Each copy, however, is much less—about $10,000. Launch costs have ranged from $0 for shuttle flights sponsored by the Space Test Program to $40,000–$70,000 for an AeroCube through the CubeSat launch provider.

A complex CubeSat such as AeroCube-3 has seven circuit boards. Ideally, each board requires three days to assemble, followed by two days for integration (i.e., harnessing), loading software, and testing. In practice, researchers have fabricated and flight-tested a picosatellite with minimal upgrades from previous designs in three months. The addition of new sensors and subsystems, however, can add significant nonrecurring development and testing time. The subsystems that require a long development time such as GPS and the advanced radio proceed in the background and are integrated on future flights as they become available.

Picosatellites have small, custom components that can be designed for rapid assembly and even mass production. The original DARPA-sponsored 1 × 3 × 4 inch picosatellites were so small that a single CNC machine setup produced multiple copies of the satellite body and battery brackets. Furthermore, the same miniature satellite was packaged so that it could be snapped together using only a few fasteners. The more capable MEPSI, AeroCube, and PSSC


"Mass production" of PicoSat bodies (left) and battery bracket (right).

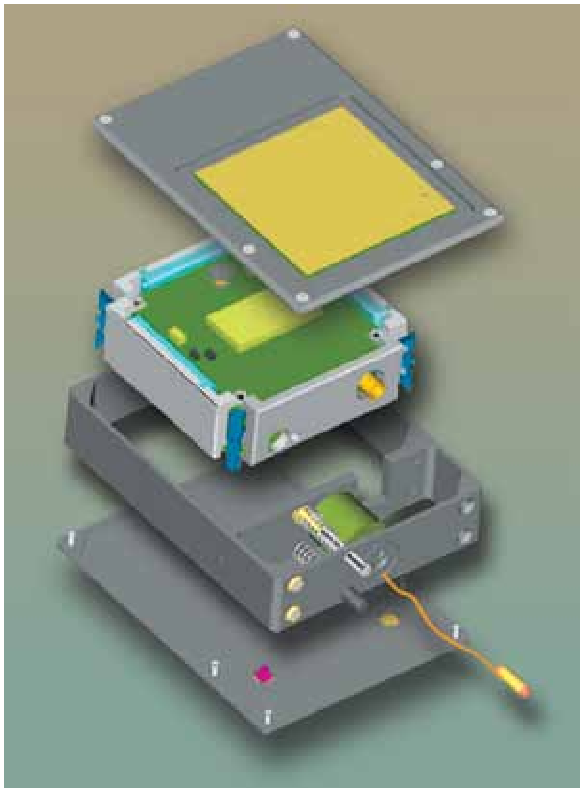
Testbed satellites had more harnesses and took more time to assemble (*Rule 3: Harnessing is the largest integration factor*). Unlike satellites assembled from parts designed elsewhere (or worse, designed to the most versatile and therefore inefficient common interface), Aerospace picosatellites were completely designed and built in-house to optimize packaging efficiency. Commercial components were used exclusively because of their higher performance and because the cost and schedule impact of radiation-hard parts is not acceptable.

Flight software presents a significant cost and schedule risk for any space mission. In designing small satellites, Aerospace researchers opted to use several distributed processors, rather than one central processor. This approach breaks up the satellite programming into a number of parallel efforts. Each satellite function has a dedicated processor that is preprogrammed. Because each function is small and well defined, the program is easy to architect and does not interact with other "task" programs except through a common serial interface shared by the multiple microcontrollers. Each microcontroller (i.e., function) is contained within a 2.2 × 2.2 inch circuit board. When a satellite needs new functions, circuit boards that perform those functions are added to the stack by means of an expandable common backplane. Conversely, if development of a circuit board falls far enough behind to miss the flight, the stack becomes one board shorter, and most of the other boards are unaffected. The added capability of on-orbit programming will further mitigate the risk to schedule, or equivalently, speed up delivery.

The single greatest impediment to rapid access to space is the availability of flights. For a lightweight secondary payload, launch costs are reasonable. However, the satellites are subject to the schedule of the primary payload. This often means that the spacecraft developers deliver the hardware on time and then wait for the primary payload to be ready after a series of unanticipated delays. Often, the vehicle provider, the primary payload provider, and the customer of the primary satellite agree to unrealistic schedules, and when they fail to meet them, the schedules for the other stakeholders are pushed back as well. Meanwhile, the secondary payload sits in storage for months, ready to go. It often takes longer to go from delivery to liftoff than it takes to develop and build the next generation of miniature satellites.

Conclusion

Aerospace has been working to develop satellites with all the capabilities one would expect from a larger spacecraft. Systems that have flown so far include reliable communications, power generation, and command and data handling. Specific components have included sensors for measuring satellite rotation rates, accelerations, geomagnetic fields, and thermal infrared radiation from Earth as well as a 640 × 480 pixel visible/near-infrared camera. The 2008 PSSC Testbed included magnetic torque coils, a solar-cell power degradation experiment, a coarse sun sensor, an Earth sensor, and two customer payloads. The 2006 MEPSI flight had three orthogonal reaction wheels and a five-thruster cold-gas propulsion unit for attitude control. Additional spacecraft hardware in the near future will include an optimized link margin radio, a megapixel imaging camera, orbit-changing propulsion, and a space-qualified GPS receiver board; anticipated software will include closed-loop attitude control.


The 250-gram PicoSat just snaps together.

The end-to-end process of designing, building, and flying miniature satellites has provided numerous benefits to the staff at Aerospace. Researchers have come to understand the intricacies of designing ultra-small spacecraft systems, learned how contractors create space systems for government customers, and relearned the importance of qualification testing and mission assurance. In these projects, the corporation's usual role of contractor oversight was turned around by 180 degrees. Such an exercise powerfully illustrates the reasons for, and the psychological responses to, the standard space systems development process.

These miniature satellite efforts have trained more than 60 scientists and engineers and provided inexpensive, rapid flight tests of commercial and mission-specific hardware and software. Aerospace will continue these efforts for cost-effective development of ultra-small spacecraft and spacecraft systems to enable new mission applications and responsive space system architectures.

Acknowledgments

The Air Force Space and Missile Systems Center (SMC/XR) and the Missile Defense Agency (MDA/STSS) have funded picosatellite development at Aerospace since 2004. The U.S. Air Force Space Test Program has integrated the Aerospace picosatellites and a nanosatellite on four launch vehicles. The authors thank these groups for their steady support, which is necessary to invent, improve, and succeed.

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Low-Power Electric Propulsion

The concept of operationally responsive access to space is leading to an increased interest in small, low-power spacecraft. Research scientist Kevin Diamant of The Aerospace Corporation's Propulsion Science department said that these spacecraft—severely limited in mass and power—could benefit from the use of low-power electric propulsion, increasing useful payload mass and enhancing mission duration and flexibility.

"The most important figure of merit for satellite propulsion is the velocity at which propellant exits the thruster. For a given amount of momentum imparted to the exhaust stream, and thereby to the spacecraft, larger exhaust velocity results in reduced exhaust mass. Reduced propellant mass can translate to reduced launch cost or additional payload. Or, for a given propellant load, larger exhaust velocity permits a greater total impulse (momentum change), which equates to greater maneuverability or longer life on station," Diamant explained.

The vast majority of satellites have relied on chemical thrusters, but chemical rocket exhaust velocity is limited by the heat released by the combustion or decomposition of the propellant. Diamant, principal investigator of an Aerospace team exploring the Hall thruster—a type of plasma-based propulsion system—said that this limitation can be removed by supplying power to the propellant from an external source, which in electric propulsion is any external electrical power source. Rostislav Spektor, senior member of the technical staff, Propulsion Science department, is a coinvestigator on the team.

"The Hall thruster may be an attractive option due to its compactness and relatively simple construction," Diamant said. "Typical Hall thruster exhaust velocities range from 15,000 to 20,000 meters per second; whereas practical values for chemical thrusters lie in the range of 2000 to 4500 meters per second."

The Hall thruster is an electrostatic thruster—a type of ion thruster that operates on the principle that a charged particle accelerates in an electric field, Diamant explained. Hall thrusters typically consist of an annular (ring-shaped) ceramic discharge channel with an electrode (anode) at one end. Propellant (usually xenon) enters through ports in the anode, and is ionized in a high-voltage discharge struck between the anode and another electrode (cathode) placed externally to the channel. The ionized gas—plasma—consists of neutral atoms, free electrons, and positively charged ions. A radial magnetic field is applied close to the channel exit. This magnetic field impedes the motion of electrons to the anode, resulting in the presence of a large electric field in the plasma. Ions are accelerated by this field, producing thrust.

Hall thrusters in the 0.4–1.4-kilowatt power range have extensive flight heritage. Approximately 250 Hall thrusters are in space, mostly on Russian satellites launched since the early 1970s, but also on several recently launched satellites built by Space Systems/Loral. The AEHF (Advanced Extremely High Frequency) satellites will carry 4.5-kilowatt Hall thrusters for orbit raising, stationkeeping, and repositioning. A 200-watt Hall thruster recently performed drag compensation for the Air Force's TacSat-2 spacecraft.

Diamant pointed out, however, that scaling Hall thrusters to power levels below a few hundred watts while preserving high average exhaust velocity and efficiency is challenging because of the need to reduce channel size to preserve ionization efficiency. Small size leads to difficulty in generation of magnetic fields with appropriate magnitude and topology, and to increased power loss from the plasma due to the larger surface area-to-volume ratio.

Rostislav Spektor and Xuan Eapen, senior research associate, investigate the origin of Hall thruster electromagnetic emission in the EMI facility.

"The cylindrical Hall thruster (CHT), invented by researchers at Princeton University Plasma Physics Laboratory, eliminates most, or all, of the inner wall of the annulus [area between two concentric circles], with the intent of boosting efficiency and life at low power," Diamant said. "A drawback of the CHT is its relatively wide plume divergence. Ions accelerated at high angles detract from thruster performance and can potentially heat and erode nearby structures."

"In an ongoing Aerospace collaboration with Princeton in the use of CHTs, we have verified that the CHT plume divergence can be reduced by approximately 25 percent and ion energy increased by 10 percent by operating an auxiliary discharge to an electrode (known as a 'keeper') placed just in front of the cathode," Diamant said. The researchers also found that efficiency from 30 to 40 percent may be achievable at power levels from 100 to 200 watts. Measurements of multiple charged ions in the CHT plume found them to be correlated with the presence of thruster erosion products.

Diamant said that in the coming year, the researchers will examine the feasibility of using a low-power Hall thruster to perform drag compensation in low orbit using propellant ingested from the atmosphere. "By decreasing altitude, smaller, lower-power, and less massive instruments can deliver capability similar to that achieved by larger satellites in higher orbits. For example, the resolution of Earth imagery is proportional to the ratio of orbital altitude to optical aperture diameter. Lower orbits enable finer resolution, or smaller, and therefore lighter and cheaper, optics."

Today's commercial Earth-observing satellites operate at altitudes from 400 to 800 kilometers and are able to resolve objects less than a meter in size. "An analysis based on assumptions appropriate for a small satellite indicates that air-breathing drag compensation using an electrostatic thruster at an altitude of 200 kilometers is feasible. Surveillance from 200 kilometers could improve image resolution by a factor of 2 to 4 over today's state of the art, or reduce instrument volume/mass by perhaps a factor of 10 or more," Diamant said.

Work for this year will include development of a microwave-powered plasma cathode. This type of cathode is expected to tolerate operation in the oxygen-rich environment of the upper atmosphere. After demonstrating extraction of sufficient electron current, the cathode will be mated with a laboratory model low-power Hall thruster, and thruster performance will be measured with relevant propellant mixtures.

Electric Propulsion Diagnostics and Modeling

Hall Current Thrusters (HCT) are emerging as the leading propulsion technology that will perform large GEO (geosynchronous Earth orbit) satellite orbit insertion and station-keeping because they significantly increase spacecraft life and allow delivery of heavier payloads to orbit for a given booster size. In 2010 the first Advanced EHF satellite is scheduled to be placed into GEO by an HCT—a first for the Air Force.

With these advantages, however, HCTs bring a new set of scientific and engineering problems. Measurements at The Aerospace Corporation, for example, have found that the electromagnetic emissions from Hall thrusters can potentially interfere with spacecraft communication during orbit raising. The origin of the troublesome strong emission in the L, S, and C communication bands (1–8 gigahertz) is yet to be determined. "Because of its unique electromagnetic compatibility facility and suite of diagnostics, Aerospace is positioned to study this radiation and develop mitigation strategies," said Rostislav Spektor, senior member of the technical staff in the Propulsion Science department. "Understanding these issues requires detailed measurements and modeling of the plume and the plasma inside the thruster."


Rostislav Spektor explains the operation of the Hall thruster to Kara Scheu, a summer undergraduate assistant.

Spektor is principal investigator of an Aerospace research project that aims to identify the origin of the Hall thruster emission in the L, S, and C bands through a combination of measurements in the Aerospace electromagnetic compatibility and near-field facilities. "Aerospace operates the leading electric propulsion laboratory in the United States specializing in the development and application of thruster diagnostics, many of which define the state of the art. While many research centers test electric propulsion devices, Aerospace provides the only comprehensive noninvasive suite of diagnostics," said Edward Beiting, senior scientist in the Propulsion Science department, who is coinvestigator of the study.

A second goal of the research is to measure distribution profiles of ion and neutral velocities, plasma density, and electron energy distribution functions inside the thruster and in the plume. This will be done by using a suite of recently developed diagnostics in the Aerospace near-field facility, which includes laser-induced fluorescence, Thomson scattering, and a retarding potential analyzer. "Success will allow, for the first time, a quantitative measure of key plasma properties in the discharge of a Hall thruster," Spektor said.

Significant progress has been made since this project first began in 2007, Spektor said. To investigate the electromagnetic emissions, Spektor and Beiting have developed new technology that allows them to measure the radiation with high spatial precision. Using this technology, they discovered that the L band (1–2 gigahertz) emission originates from the cathode. This has implications for HCTs as well as the XIPS (Xenon Ion Propulsion System) ion thrusters used on the Wideband Global Satcom spacecraft, since both types of thrusters are using a cathode for plume neutralization. Further studies are being conducted to identify the sources of the S (2–4 gigahertz) and C (4–8 gigahertz) band emissions, and to understand the underlying physical processes that cause this radiation.

The newly upgraded laser-induced fluorescence (LIF) diagnostic has recently been used to study the Princeton Plasma Physics Laboratory cylindrical Hall thruster—Princeton and Aerospace have collaborated on the uses of this novel low-power thruster. The thruster was successfully fired for the first time in the Aerospace near-field facility. Spektor said that the two-dimensional velocity profile inferred from the LIF measurements in the plume of the cylindrical Hall thruster led to important insights into the physics of this innovative device.

Also being researched is electron dynamics. "Electrons play an important role in establishing operating parameters in a Hall thruster," Spektor said. He added that it has been recently proposed that electrons are not thermalized in some regions of the plasma discharge. He and Beiting are developing Thomson scattering diagnostics and a miniature retarding potential probe to measure this nonthermal electron behavior. The Thomson scattering method is widely used to investigate fusion plasma, but has not yet been applied to HCTs. "Verification of this behavior will be a major contribution to the scientific community and may have practical implications to HCT design," Spektor said.

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Patents

D. A. Ksienski, J. P. McKay, S. S. Osofsky, K. S. MacGowan, and G. M. Shaw, "Higher-Order Intermodulation Reduction Using Phase and Angle Smearing," U.S. Patent No. 7,420,508, Sept. 2008.

Multiple, simultaneous antenna beams required in communication systems are often achieved using active phased arrays. A common problem encountered in these systems is the generation of intermodulation product beams due to nonlinear effects. This patent describes a method for reducing intermodulation beams. It starts by identifying one or more higher-order intermodulation beams that need to be reduced and determining acceptable degradations for the fundamental beams associated with them. Next, phase and angle beam-smearing parameters are identified that would reduce the intermodulation beams with acceptable degradation to the fundamental beams. These parameters are then used to apply a beam-smearing phase distribution to an array along with a beam-steering distribution. This invention can be used for satellite antenna arrays or any application that generates multiple simultaneous beams in the presence of nonlinear effects.

H. S. Hou, "Merge and Split Discrete Cosine Block Transform Method," U.S. Patent No. 7,437,394, Oct. 2008.

Fast transform methods for the compression and decompression of data entail separating and combining data blocks in the transform domain and inversely transforming them back to the spatial or temporal domain. In the process, however, the quality of the transformed data is degraded. This invention is aimed at decreasing the degradation caused by the fast forward process. Input data in the temporal or spatial domain during either the split or merge radix-2 forward processing step first undergoes transform processing followed by combinational processing. In the split transform process, whole transformed data are split into two halves using combinational processing in the transform domain. In the merge transform process, these two halves are merged using combinational processing in the transform domain. The combinational processing enables true recursive splits and merges in the transform domain without data degradation.

G. L. Lui, K. Tsai, and M. K. Sue, "Automatic Gain Control 16-ary Quadrature Amplitude Modulation Subsystem," U.S. Patent No. 7,450,670, Nov. 2008.

In a digital data transmission system that uses amplitude and phase modulation, such as the 16-ary quadrature amplitude modulation (16-QAM), the performance of the receiver is essential. However, if the receiver is not catching the large signal-to-noise ratios accurately enough, communication is compromised. The invention concerns a baseband automatic-gain-control subsystem that tracks the amplitude of signals with large signal-to-noise ratios as a subset of all of the signals in the constellation space. This information helps determine the amount of automatic gain control needed to uniformly improve reception of all received signals. By averaging only the signals with large signal-to-noise ratios, a demodulator can provide automatic gain control up to 1.0 dB better than a demodulator that averages all of the amplitudes of all of the received signals. The technique can be implemented with only modest modifications to an error detector in a conventional design.

T. Nguyen, J. Yoh, A. Mathur, and G. Goo, "Random Walk Filter Timing Recovery Loop," U.S. Patent No. 7,469,026, Dec. 2008.

In a communication receiver, a received RF signal is tracked and demodulated to generate a baseband signal waveform that contains bit transitions to help the demodulator lock on to the data bit stream; however, channel noise can corrupt the bit transition timing and cause the demodulator to lose track of the bit stream. Timing recovery loops are used to track bit transitions and reacquire the bit stream, but most conventional algorithms are still subject to long reacquisition time and frequent bit timing lock drop in multipath environments. This invention uses a random-walk filter with a settable error threshold that allows for adaptive synchronization in the timing recovery loop. When the filter's lead/lag counter output exceeds the threshold, the estimated bit transition time can be adjusted, allowing for its continued synchronization to the signal waveform. As such, the random-walk filter continuously adjusts the estimated bit transition time to maintain an accurate bit timing lock. This timing recovery loop can be used with low-power technology and is applicable to a wide range of modulation schemes for enhanced mobile communications.

A. O. Okorogu, "High Power Optical Fiber Laser Array Holographic Couplers," U.S. Patent No. 7,469,082, Dec. 2008.

Current methods of launching high-power pump or laser light into fibers can adversely affect the mechanical integrity, power requirements, and system complexity, which would require redesigning the fiber coupling structure, especially for coupling an array of laser diodes. This patent describes a novel method of coupling high-power laser light or an array of laser diodes into double-clad Yb and co-doped Er-Yb fibers for much higher levels of light amplification. It is based on the application of mature volume holographic optical element (HOE) technology, which can be fabricated in any of the commercially available high-efficiency photosensitive holographic recording materials. This HOE coupler does not require mechanical etching of coupling structures or embedding of micromirrors within the fiber cladding. It consists of stripped double-clad fiber sandwiched between transmitting and reflecting HOEs. The device offers advantages over current coupling schemes, especially ease of coupling, high angular and spectral selectivity (filtering), high optical power (concentration), light weight, thin aspect (~15 mm), low cost, high coupling efficiency, insensitivity to misalignment, and simplicity of direct coupling into fibers with minimum perturbation of fiber structure and manufacturability. It has a unique advantage of being a truly universal coupling scheme for all types of inner cladding shapes, sizes, and designs.

W. E. Lillo, K. J. Scully, and C. D. Nealy, "Multitarget Tracking Antispoofing Receiver," U.S. Patent No. 7,471,238, Dec. 2008.

This GPS receiver improves tracking in the presence of jamming or spoofing signals by coupling the GPS signal with an inertial navigation system that has an inertial measurement unit (IMU). When it encounters an interfering signal, the receiver maintains track on the target signal by tracking the code phase, carrier frequency, and power. Conventional multitarget tracking algorithms are used to distinguish among the competing signals. When signal tracks have been sufficiently resolved, the tracking information is fed to a prefilter and ultimately to the navigation filter. The IMU information allows for a narrow gate for the true signal. The crossing of tracks can be anticipated and resolved without losing track on a desired object. The greater power of the spoofer is a distinguishing characteristic and actually hinders its ability to interfere. Therefore, the multitarget tracking receiver can maintain a lock on a target signal, even in the presence of crossover spoofing signals.

M. A. Zurbuchen, "Automated Sectioning Tomographic Measurement System," U.S. Patent No. 7,507,145, Mar. 2009.

There is frequently a need to image the internal structure of an object—particularly at the scale of 200 nm to 10 mm—to determine failure mechanisms. Typically, a sectioning approach is used in which successive layers are removed in very thin slices; however, this approach poses difficulties in terms of accuracy and resolution. This invention describes a tomographic measurement system that integrates the processes of grinding and polishing a 3-D cross section and imaging it in digital form so that it can be stored in a computer. The system includes a number of abrasive grinders, a wash station for washing and etching the object for improved imaging, an imaging station that captures both the object and a marker that indicates the depth of grinding, and a robot for moving the fixture between the grinder, washer, and imager. A simple edge-detection algorithm enables computer control software to recognize the marker reading in a given image; the marker can therefore be used to stop the automated serial sectioning at target depths. The system can process objects on scales as small as 2.5 nm.

R. B. Dybdal and D. Pidhayny, "Methods and Systems for Tracking Signals with Diverse Polarization Properties," U.S. Patent Nos. 7,518,551 and 7,551,134, Apr./June 2009.

Antennas are generally designed to receive radio frequency signals with a specified polarization, but in practice, the polarization of received signals does not always conform to the specified value. The resulting polarization mismatch reduces signal strength, degrading system sensitivity; in extreme cases, the antenna tracking performance can become unstable, resulting in a loss of antenna tracking and signal reception. This invention describes a system for antenna tracking that measures and processes orthogonally polarized signal components. The processing serves two objectives. The first is to minimize polarization mismatch loss, thereby preserving full system sensitivity. The second is to avoid unstable antenna tracking and the resulting signal loss while optimizing antenna tracking performance. The antenna tracking design operates in a closed-loop manner that can dynamically follow changes in the received signal's polarization values.

J. T. Dickey and T. T. Lam, "High Density Electronic Cooling Triangular Shaped Microchannel Device," U.S. Patent No. 7,523,780, Apr. 2009.

Cooling technology for microelectronic products is being pushed to the limit by the increasing number of components mounted on high-density electronic chips. This patent describes a pumped-fluid loop with triangular microchannels arranged in a sawtooth configuration. This orientation maximizes the absorption of thermal energy by the fluid and can increase the heat-transfer coefficient by 4.5 W/cm^2/°C. The microchannels have a large heat conduction area that effectively spreads heat throughout the device, resulting in low surface temperatures. The triangular shape allows for a large number of microchannels to be packed together, thereby enabling a high flow rate of the pumped fluid. The sawtooth configuration allows for high heat conduction through an interstitial area, enabling heat to travel freely to the entire convective surface area. The reduced and uniform temperature serves to increase reliability and component life.

M. A. Rolenz, "Laser Communications Crosslink System," U.S. Patent No. 7,526,206, Apr. 2009.

Traditional satellite crosslinks can adversely increase the complexity and power requirements of a space system. This laser crosslink system mitigates these problems. A sigma-delta modulator converts an analog input to a binary data stream that is sent to a laser transmitter. The data stream is received by a laser receiver and sent to a digital filter that generates a digital output. Thus, the system enables direct laser modulation of binary signals. Because it combines the analog-to-digital conversion and transmission steps, the system requires fewer parts and power requirements than a comparable system based on phase-shift keying. The use of a sigma-delta modulator prior to transmission also reduces the roll-off requirements for anti-aliasing filters in the analog-to-digital converter, which in turn reduces manufacturing tolerances and required performance.

F. E. Livingston and H. Helvajian, "Pulse Modulation Laser Writing System," U.S. Patent No. 7,526,357, Apr. 2009.

Laser processing and micro/nanomachining of materials and components are generally limited by the relative lack of precision photon flux control, particularly when the samples are in motion or constructed of multiple heterogeneous materials. This pulse-modulated laser writing system overcomes this problem by enabling the position-synchronized delivery of discrete, preprogrammed laser pulse scripts to a substrate with high fidelity during patterning and motion sequences. The laser pulse scripts are synchronized with the motion-control file so that every laser-irradiated spot within the sample will receive exactly the photon dose and intensity pulse sequence necessary, despite the evolving material properties or changes in velocity of the sample. The laser processing platform is highly versatile and can seamlessly and dynamically merge a diverse array of other process scripts, including material type, surface topography, prior photon dose history, and the desired type of material processing, along with automated calibration routines and diagnostic tests. The laser technique can be readily applied to fundamental investigations of complex laser-material interaction phenomena, and the architecture can be easily integrated into laser-material processing schemes for commercial and industrial applications.

G. L. Lui and K. Tsai, "Quaternary Precoded Continuous Phase Modulation Soft Bit Metric Demodulator," U.S. Patent No. 7,529,323, May 2009.

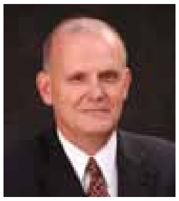
A quaternary soft-bit metric (QSBM) demodulator uses the maximum-likelihood sequence estimation (MLSE) Viterbi algorithm to generate log-likelihood ratios. The demodulator can be used for precoded quaternary Gaussian minimum shift keying (GMSK) signals and, more generally, for precoded quaternary continuous phase modulation (CPM) signals. It is implemented as a streamlined MLSE Viterbi algorithm that requires no memory elements for storing the survivor path states. In a GMSK system, the bandwidth-time product of the Gaussian premodulation shaping filter is 1/3, the modulation index is 1/4, and the receiver uses three matched filters. The demodulator can be used either in a stand-alone uncoded CPM system or in a coded CPM system in conjunction with some forward error-correction scheme such as the classical rate-1/2 convolution code with MLSE Viterbi decoding. In the latter case, the demodulator can improve the signal-to-noise ratio by 3.0 decibels over hard-decision error-correction decoding.

A. O. Okorogu, "High Power Optical Fiber Laser Array Holographic Coupler Manufacturing Method," U.S. Patent No. 7,551,818, Apr. 2009.

This cost-effective method of manufacturing universal or versatile holographic optical element (HOE) couplers requires no mechanical etching or embedded micromirrors and offers easy mechanical coupling, insensitivity to misalignment of laser diodes, and high-angular and spectral filtering selectivity. The process entails simulating a laser diode or an array of diodes with varying divergence angles by placing a slit or slit array and/or an array of microlenses in the path of collimated object beams, which generate spherical wavefronts with divergence angles of various magnitudes. The position of the slits represents the lateral location of the laser diodes in the arrays that are to be coupled into the fiber. The separation of the slits is the exact separation distance of the intended diode in the fiber scheme. A computer controls the lateral position of each slit or microlens point and incrementally steps light from there to illuminate the holographic film plate where it intersects with a reference spherical beam. The intersection of the beams creates a varying fringe structure called a "chirped" grating. Creation of the chirped grating within the HOE increases the coupling efficiency of the laser diodes into a supported cladding mode of the fiber to greater than 90 percent. This would be impossible with any coupler that does not account for sources with varying divergence angles.

Contributors

Creating An Agile, All-Space Architecture



Thomas C. Adang, Systems Director, Operationally Responsive Space Office (ORS), joined Aerospace in 2000 after a 27-year military career with broad experience in aircraft and space vehicle development and operations. Since joining Aerospace, he has supported the National Reconnaissance Office, the National Oceanic and Atmospheric Administration (including a two-year federal appointment), and DOD. Adang has a Ph.D. in atmospheric sciences/remote sensing from the University of Arizona (thomas.c.adang@aero.org).

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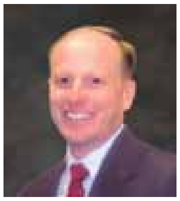
Agile Space Launch



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Developing a Responsive Ground System Enterprise

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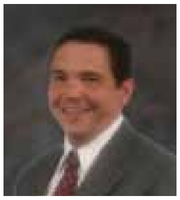
Open Architectures and Standards for Agile Space



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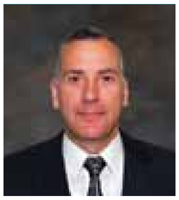
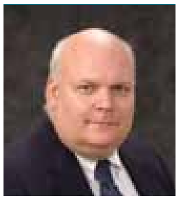
A Flexible Satellite Command and Control Framework



Thomas J. Sullivan, Senior Engineering Specialist, Ground Systems Department, joined Aerospace in 2005 after serving in the Air Force, where he managed ground systems engineering and development in the commercial sector. Sullivan currently serves as the technical director of the Aerospace Ground Systems Laboratory in Chantilly, Virginia, supporting the National Reconnaissance Office, the Air Force Space and Missile Systems Center, and the Operationally Responsive Space Office in the application of information technologies to space ground systems. He has a master's of engineering in space operations from the University of Colorado, Boulder (thomas.j.jsullivan@aero.org).



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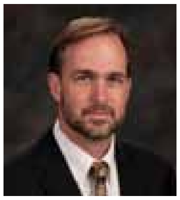
Building Miniature Spacecraft at The Aerospace Corporation



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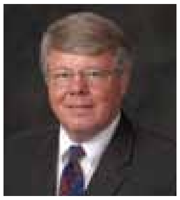


Siegfried W. Janson, Senior Scientist, Mechanics Research Office, is the co-editor of *Small Satellites: Past, Present, and Future* (The Aerospace Press/AIAA, 2009). Since joining Aerospace in 1987, he has played a key role in creating and then shaping and directing the United Kingdom Foreign Comparative Test program for the evaluation of British ion engines for eventual use on U.S. satellites. His technical expertise includes micropropulsion and microtechnologies for future space systems. Janson has a B.S. in aeronautical engineering from Rensselaer Polytechnic Institute and a Ph.D. in aeronautical engineering from Cornell University (siegfried.w.janson@aero.org).

The Aerospace Ground Systems Laboratory

Innovators of Computing Solutions for National Security Space

Thomas Sullivan and Kenneth Austin

The Aerospace Ground Systems Laboratory (GSL) in Chantilly, Virginia, has provided numerous government customers with invaluable, hands-on expertise for all aspects of ground system software and computing architecting, design, development, testing, and operations since 2003. These customers include the Air Force Space and Missile Systems Center, the National Reconnaissance Office, NASA, and the newly formed DOD Operationally Responsive Space Office.

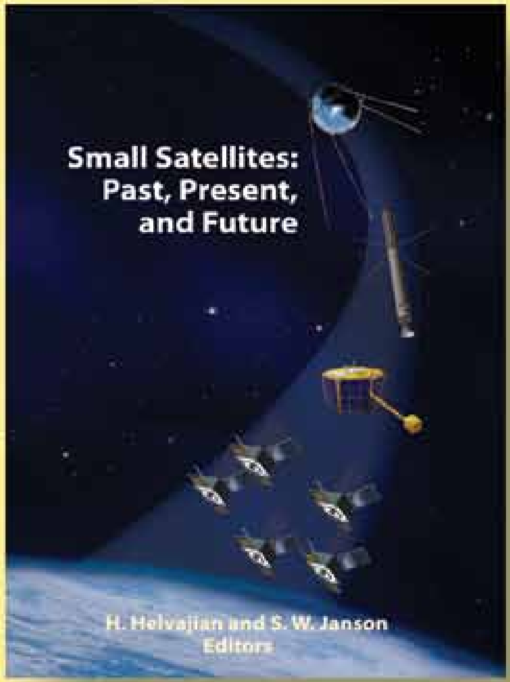
The GSL offers concept exploration and independent verification and validation of new ground system architectures for satellite command and control, mission planning, signal processing, mission data processing and distribution, and information operations. Aerospace employees supporting the GSL provide analysis, development, and independent assessments using the latest in information technology to support government acquisition decisions.

Quick prototypes in particular are often instrumental in answering specific technical questions that arise for the government during the planning and acquisition process. For example, during 2008–2009, the GSL has supported prototypes for the application of Web 2.0, computer virtualization, mobile computing, and service-oriented architecture techniques and technologies.

The GSL typically uses the latest in information technology hardware and software tools from multiple unclassified and classified networks to develop these prototypes and concepts, which are designed to meet unique customer requirements. The work includes analyzing and testing government-developed software systems and investigating the application of commercial technologies and products to address mission-critical government requirements.

The GSL is part of the Aerospace Engineering and Technology Group, Computers and Software Division, and offers the dedicated resources needed to provide the U.S. Government with the critical expertise in ground software and computer engineering that can only come from hands-on experience in a laboratory. National security space organizations across the government have effectively used Aerospace GSL capabilities to support current and future space ground system acquisitions.

New Titles from The Aerospace Press



Small Satellites: Past, Present, and Future

Henry Helvajian and Siegfried W. Janson, editors

The first book to describe the state of the art in microsats, nanosats, picosats, and CubeSats—and the possible missions they can perform.

More than two dozen internationally renowned contributors provide 50 years of historical context and a comprehensive overview of small satellite technologies, missions, and architectures, allowing the reader to learn how various small satellites are designed, fabricated, and flown. New types of space architectures, missions, and satellite designs are presented, including the use of mass-produced small satellites in large constellations and local clusters. Readers will also learn about new materials and cost-effective manufacturing techniques for mass-customizable small satellites.

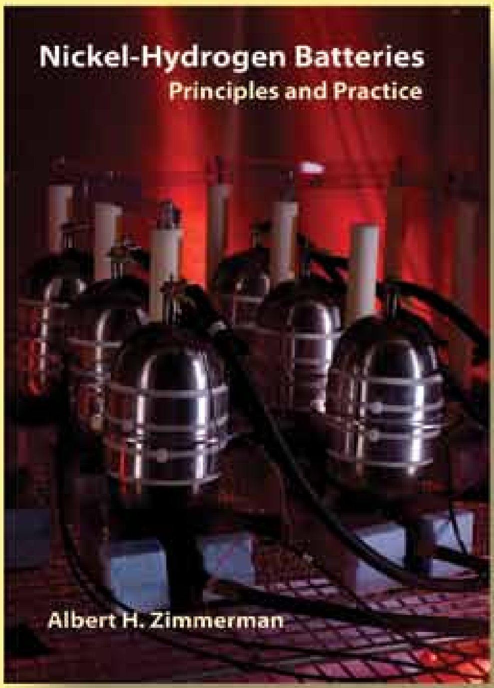
Topics include the Clementine, Mini AERCam, SNAP-1, MOST, Proba, INDEX, and TUBSAT missions; the Air Force Academy, Naval Academy, and Naval Postgraduate School satellite programs; the role of AMSAT; the legacy of MicroStar; the history of small satellites; the origins of CubeSat; co-orbital assistants; the Aerospace PicoSat, MEPSI, and AeroCube missions; and technology development for formation flight, tracking, networking, mass production, and spacecraft operations.

Nickel-Hydrogen Batteries: Principles and Practice

Albert H. Zimmerman

Nickel-hydrogen cells provide one of the longest-lived and most reliable rechargeable battery systems ever developed. Widely used in space power systems, they are generally considered well worth the cost because of their exceptionally long life. This book provides an in-depth view of nickel-hydrogen cell technology: how it was developed, how and why it works, how to get the most from it, and what can go wrong if it is not properly managed.

The book is organized into three parts that provide a balanced picture of the development, principles of operation, and key concerns regarding the use of nickel-hydrogen technology in satellite power systems. Part I provides an overview and historical discussion of the technology, along with a summary of key performance traits. Part II explores fundamental principles, and includes chapters on the nickel electrode, the separator, the hydrogen electrode, and various performance models. Part III focuses on the application and practice of using nickel-hydrogen technology, and addresses issues such as charge management and thermal control. Also included in this section are chapters on various degradation and failure modes and on methods that have been developed for analyzing cells to deduce why they eventually fail.



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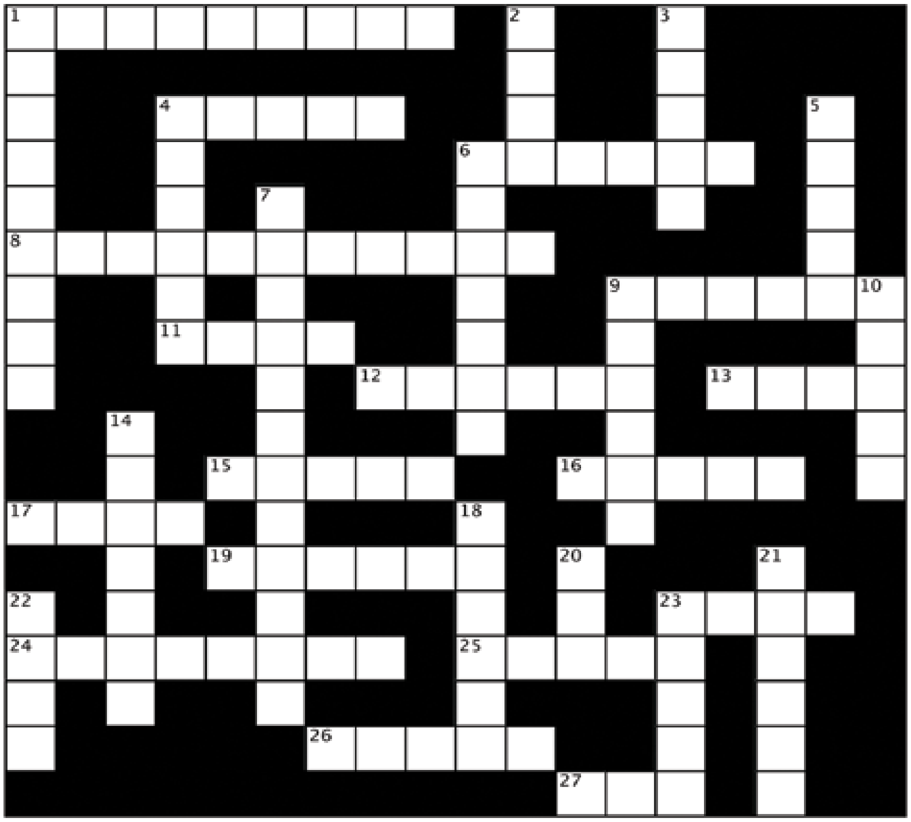
The Crosslink Crossword

Across

1. Tall hat
4. Meals for a fee
6. Leash
8. User-friendly toy spec
9. U.K. cell
11. Stadium section
12. One who alters
13. White-collar workspace
15. Marketing for a few
16. Sword tip
17. Main road
19. Out-of-the-way
23. Film spool
24. Diplomatic code
25. Antelope playground
26. Police staff
27. Door opener



Down

1. Stash
2. Sydney greeting, "G'day, ____"
3. Good quality
4. Allocate
5. Runway walker
6. Bane of L.A.
7. Smarts
9. It named The Fairest
10. CD player button
14. Hookup
18. Non-U.S. measure
20. Make tracks
21. Purveyor of pretzels
22. Willing to listen
23. Race with baton

Most puzzle words and clues are from articles in this issue. The solution is on the Crosslink Web site: http://www.aero.org/publications/crosslink/.