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**From the President’s Desk**

This special issue of Crosslink commemorates the 45th anniversary of The Aerospace Corporation. It focuses on the past five years, a time of significant transition.

During this time, much has affected our industry, our company, and our lives: the war on terrorism, the Columbia tragedy, the conflict in Iraq. These years brought a new vision for NASA, a broader mission for NOGTA, a reorganization of Air Force Space Command, and a restructuring of the national intelligence agencies resulting in the formation of the office of the Director of National Intelligence. Several heritage launch vehicle programs came to a close, with the last launches of Atlas II, Titan II, and the Inertial Upper Stage. We marked the death of Ivan Getting, the founding president of Aerospace, and the beginning of my tenure as President and CEO.

At the same time, Aerospace supported the growth and refinement of several important national security space programs, including the Evolved Expendable Launch Vehicle, the Wideband Gapfiller Satellite, the Space-Based Infrared System, the next-generation GPS, the National Polar-orbiting Environmental Satellite System, and several NRO programs. We have acquired greater prominence in the program oversight process, and have assumed greater accountability for our role. Our commitment to mission success should be evident to anyone reviewing the achievements of the last five years.

To put these achievements into a historical perspective, this issue of Crosslink offers some reflections by Executive Vice President Joe Straus on some of the more significant trends that have shaped the industry and Aerospace’s responses to them. A report from recent Trustees’ Distinguished Achievement Award winners and a synopsis of intellectual property management provide further insight into the specialized work that makes Aerospace such an asset for the national security space community.

Coincidentally, this year marks the fifth anniversary of Crosslink. Accordingly, this edition features a selection of previously published articles and news briefs. An index to all articles that have appeared in Crosslink is also included. Collectively, they cover the achievements of the last five years.

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Aerospace has a formal process to explore and develop ancillary applications for technology originally developed to support the national security space community.

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**Maggie Award**

The Summer 2004 Crosslink, “Remote Sensing,” received the magazine’s third consecutive Maggie Award from the Western Publications Association as the best semiannual/three-time-published magazine west of the Mississippi River.
**New Tools for Testing Antennas**

A new testing facility will enable Aerospace to provide more accurate and secure assessment of large, complex satellite antennas. The near-field range antenna uses a large planar scanner to characterize the radiation patterns of antennas and scale models. It’s also used to investigate new measurement techniques and methodologies. Specialized data-processing routines enable the Aerospace range to capture an antenna’s entire radiation pattern—an achievement that would be impossible using conventional planar near-field techniques, said facility director Paul Rousseau.

The previous facility, though much smaller, made key contributions to a National Reconnaissance Office program, determining, for example, that the far sidelobes (unwanted spikes in the radiation pattern) of an antenna system were caused by electromagnetic scattering from struts. Mock-up measurements developed at the range also helped validate a numerical analysis, saving the program an estimated $5 million, Rousseau said.

The near-field range became operational in October 2001, but additional enhancements are planned. New material for absorbing microwaves will be installed, with slightly larger dimensions to allow measurements at lower frequencies. Researchers will also install a larger 12- by 12-foot scanner that will enable them to analyze antennas up to 10 feet in diameter. Upgrades are also planned for the facility’s compact range, which uses a large parabolic reflector to simulate the long-range performance of a satellite antenna. (Winter 2001/2002)

**Galileo Goes Forward**

The European Union (EU) has decided to press forward with plans to develop Galileo, a European version of the Global Positioning System (GPS). The European Commission approved funding for the project despite resistance from the United States, which sees “no compelling need” for it, according to a U.S. State Department announcement.

The development phase of Galileo is expected to run from 2002 to 2005, allowing researchers to test the technology on orbit before implementing the complete, 30-satellite constellation. A deployment phase will follow, leading to a full operational capability in 2008.

The Aerospace Corporation has been helping define U.S. position with respect to Galileo. For example, Aerospace analyzed potential interference from GPS to Galileo’s proposed navigation signal structure and assessed options for making the time and space reference frames interoperable. These reference frames define time and position for all systems and are used for flight operations. The navigation signals provide ranging signals, tied to the time and space reference frames, that allow a receiver to determine its position and time. The Aerospace work had two goals: to prevent GPS and Galileo from adopting signals that interfere with each other, and to identify opportunities for making the signals and reference frames interoperable. By making them interoperable, the United States and EU would enable manufacturers to build inexpensive receivers that can simultaneously use signals from both systems.

After identifying a range of approaches and assessing their technical and practical impact, Aerospace recommended that each system develop and maintain its own reference frames but provide users with the data needed to remove intersystem errors. Greater levels of coordination were viewed as technically desirable but would have required revisions of U.S. and EU policy. Aerospace also assessed several alternative Galileo signal designs in light of technical and national objectives. The assessment identified candidate signals that would be compatible with existing GPS civil signals and that provide the opportunity for establishing a new common standard structure for future civil satellite navigation signals. These recommendations were provided to the GPS program office for eventual use by the Defense and State Departments.

The EU has pledged that Galileo will be a civil program under civil control, independent of, but interoperable with, the civil components of GPS. Although the initial funding approval freed up 4.5 million euros, the total system cost is estimated at 3.4 billion euros. (Summer 2002)

**Researchers Track Mir’s Reentry**

After 15 years in orbit, the Mir space laboratory took a fiery plunge toward Earth, and Aerospace was on hand to examine the event. The Center for Orbital and Reentry Debris Studies (CORDS), under the direction of William Ailor, has been gathering data to characterize how Mir broke up and what parts survived reentry.

Mir disappeared into the South Pacific, so the prospects for ex- amining debris are naturally limited. But Ailor’s team has gathered useful details from a wide variety of sources—including tracking data, video clips, eyewitness reports, and radar measurements. Using this information, the researchers have been reconstructing the final descent. NASA has contracted Aerospace to perform this analysis.

The information should hold immediate benefits for designers and operators of space systems, who need to understand what will happen to a satellite or space vehicle when it reaches the end of its mission life. Knowledge of how complex structures disintegrate during reentry can also help designers optimize satellite configuration. “If you have critical components, and you really want to make sure they get cooked on the way down,” said Ailor, “you can put them in places where you know they’ll disintegrate. Similarly, if there are things you want protected, you can keep them on the interior, keep heating to them low.”

Ailor further noted that satellite operators are increasingly being asked—though not yet required—to examine reentry risk. In fact, Aerospace has been working with NASA to develop thresholds and guidelines for satellite deorbiting. “Basically, if your footprint on the ground is bigger than eight square meters, you’ll need to exercise a controlled deorbit,” Ailor said.

CORDS also helped NASA in reconstructing the demise of the Compton Gamma Ray Observatory, which was successfully brought down in June 2000 (see Crosslink, Winter 2000/2001). Of course, that observatory weighed only 17 tons, whereas Mir—the “granddaddy of them all,” as Ailor puts it—weighed about 44 tons. Moreover, the observatory left orbit in a very precise manner, coming down “right on the money,” said Ailor. Mir, in contrast, fell slightly ahead of its mark, primarily because Russian controllers were very conservative in their calculations.

Aerospace provided technical support for the reentry. Wayne Hallman is leading the Mir trajectory reconstruction effort. (Summer 2001)

**Amazing MEMS**

Microelectromechanical systems (MEMS), machines so tiny they cannot be seen with the naked eye, are quickly gaining notoriety for their capability and versatility in a variety of areas. MEMS can be used to detect environmental pollutants, monitor the health of a premature newborn, sense an impending car crash and deploy the air bag, and be “woven” into the clothes of soldiers on the battlefield (where the sensors would warn against an attack by chemical or biological weapons).

A more aggressive use of MEMS is the potential for manufacturing mass-produced, 1-kilogram-class nanosatellites with microelectronics-processing technology.

More than 30 Aerospace scientists are involved in MEMS research, including Henry Helvajian of the Aerospace Center for Microtechnology and the editor of Microengineering Aerospace Systems. Aerospace researchers sent aloft a MEMS experimental testbed on the space shuttle Columbia last year. Data from 30 of the devices were analyzed to see how their performance varied during launch, orbit, and reentry, compared with their performance in preflight tests. One device, designed and built by Aerospace, contains 15 microthrusters, which act like 15 individual solid rocket motors. The usefulness of MEMS in space has yet to be fully realized, and the analysis by Aerospace was the first systematic testing of MEMS in that capacity. Another experimental MEMS test mission, planned for 2001, will involve the International Space Station. (Summer 2000)

**GPS for the Military and Civilians**

The fourth in a series of U.S. Global Positioning System (GPS) replacement satellites, GPS IIR4, was launched aboard a Delta II from Cape Canaveral May 10, 2000. Aerospace reviewed the hardware, software, and procedures, and verified that the vehicle was ready for launch. Aerospace developed the fundamental concept of GPS for the Air Force in 1963. Today, GPS, a constellation of 28 navigational satellites that orbit 11,000 miles above Earth, is used increasingly by civilians. Civilian owners of GPS receivers found their systems significantly more accurate as of May 2, 2000. That day, the U.S. military, which retained its right to selectively deny the GPS signals over any given region, turned off its intentional degradation of GPS satellite signals by the military. The military will, however, retain its right to selectively deny the GPS signals over any given region.

Civilians use GPS for many purposes, including search and rescue operations and airframe and ground-vehicle navigation (GPS sensors placed in cars enable drivers to use the Internet to navigate). Unscrambling the signals should benefit the GPS industry, which is expected to grow to $16 billion in the next three years. (Summer 2000)
Improving GPS Theater Support

In preparation for Operation Iraqi Freedom, the 14th Air Force tasked the 50th Space Wing to develop and deploy an extended type of GPS support to accommodate the intensive precision munitions push. Aerospace supported the 2nd Operations Squadron (2SOPS) by developing an innovative technique to enhance theater accuracy and integrity. As explained by P.J. Mendicki of the Navigation Division, the new technique is a variation of the GPS enhanced theater support (GETS), which was implemented just a few years ago. Using traditional GETS, field personnel would contact 2SOPS with a generalized target location and strike time window. The 2SOPS office would predict which satellites would be overhead, monitor their performance, and update their broadcast navigation message. The system worked well, but the improvements were short-lived, lasting only about an hour, and planning required adequate advance notice. “Traditional GETS,” said Mendicki, “is very limiting—we can’t do much with it after it’s been calculated.”

Aerospace proposed a new approach. “We know when satellites will be visible to the theater, and we control our contact schedule, so why not proactively schedule uploads to maximize theater performance?” Mendicki asked. Thus, those satellites approaching the area would be uploaded with a new navigation message shortly before entering the theater of operations. “Rather than do it ad hoc, or on the fly, we made it a routine scheduled activity, which helped smooth out operations.” As an added bonus, he said, “the new approach allows war planners to attack targets of opportunity,” such as those that began the air campaign, the old GETS approach could not.

Aerospace went to 2SOPS with the proposal, and within four days the 2SOPS team tested this new tactic with the operational GPS constellation. The results were so promising that the technique was implemented 48 hours later in support of the opening salvos of the air campaign. Throughout Operation Iraqi Freedom, in which thousands of GPS-guided munitions were employed, the GPS in theater accuracy was improved by more than 20 percent. “It worked out very well,” Mendicki said.

Mendicki has since been researching whether the technique would yield similar results in other theaters, and how it might be applied during two simultaneous conflicts. “Geography may limit our support to other theaters,” he said, “but overall, it looks good.”

Satellite Sentinels

Spurred by a need for greater “situational awareness” in space, the Air Force is moving ahead with development of the Space-Based Space Surveillance (SBSS) system. The Initial Operating Capability of this system has been used to track, identify, catalog, and observe man-made objects in space, day or night, in all weather conditions. The complete system will enable key warfighter decisions based on collection of data regarding military and commercial satellites in deep space and near-Earth orbits without the inherent limitations (e.g., weather, time of day, location) that affect ground systems.

“The SBSS system will provide the ability to find smaller objects, precisely fix and track their location, and characterize many objects in a very timely manner,” said Dave Albert, Principal Director, Space Superiority Systems, and Jack Yeatts, Future System Director. During the creation of the program, Aerospace performed key mission-assurance risk assessments for the Air Force Space and Missile Systems Center (SMC). During the technical requirements development and source selection, “Aerospace’s technical evaluations led to convincing risk mitigation actions on the launch vehicle and the focal planes,” said Arthur Chin, SBSS Program Lead.

A new operational pathfinder, which will operate in low Earth orbit, has completed source selection and is scheduled for launch in June 2007 to significantly improve the current on-orbit capability. It will be launched by a Peacekeeper space-launch vehicle that is under SMC/Aerospace mission assurance and launch-readiness review. The follow-on constellation will begin acquisition in 2005, with initial operational capability slated for 2012. (Summer 2003)

Aerospace Aids Shuttle Investigation

Scientists from The Aerospace Corporation provided technical support and analyses to NASA earlier this year in its investigation of the space shuttle Columbia accident. William Ailor, director of Aerospace’s Center for Orbital and Reentry Debris Studies (CORDS), testified before the Columbia Accident Investigation Board in a closed session March 13 on the history of space hardware reentry and breakup and what can be learned about the breakup from debris recovered on the ground. Ken Holden, general manager of the Aerospace Launch Verification Division, briefed board members May 21 on the corporation’s basic launch verification process.

The disintegration of the Columbia occurred February 1 during the reentry phase of the Space Transportation System (STS)-107 mission. The resulting debris field has characteristics similar to those seen for other reentry breakups. Ailor said, Aerospace has been involved in analyses of reentry breakups for many years and established CORDS in 1997 to lead this work.

Ailor’s testimony covered the kinds of evidence of the cause of the accident that might have survived the extreme reentry environment and included recommendations for how individual pieces of debris and the distribution of debris within the debris field might help reconstruct events leading to the accident. The investigation board invited Ailor to provide a similar briefing to a public session, broadcast live on CSPAN March 17. Aerospace scientists, including Ailor, Douglas Moody, Gary Stockel, and Michael Weaver, later visited the hangar where the recovered debris was cataloged to evaluate the debris and provided recommendations for analysis.

During his briefing to the board, Holden described the elements of the launch verification process, which Aerospace uses to provide unbiased independent technical assessments to support all Air Force space launches. “Unlike conventional space launch verification processes, Aerospace’s centers for orbital and reentry debris studies (CORDS) provided independent technical assessments to support all Air Force space launches. “Unlike conventional space launch verification processes, Aerospace’s

Satellite Sentinels

When the twin towers of New York’s World Trade Center collapsed after the terrorist attacks on September 11, 2001, public officials faced the formidable task of sifting through the wreckage to find victims and collect forensic evidence. The Aerospace Corporation immediately offered its assistance and resources. As a result, a remote-sensing instrument developed by Aerospace helped generate and analyze data to support the investigation.

The instrument, known as the Spectrally Enhanced Broadband Array Spectrograph System (SEBASS), is a midwave and long-wave hyperspectral imager optimized for airborne sensing. It was flown over the site in October to characterize the distribution of gas and materials.

The information was used to confirm or refute the presence of asbestos in and around the wreckage area as well as the landfill where the debris was deposited. The concentration of asbestos was not high enough for the sensor to detect, but the distribution of fiberglass (which would be expected to have a distribution pattern similar to that of asbestos) was mapped out. SEBASS also detected and mapped the spread of freon and ammonia gas. (Winter 2001/2002)

Popular Science Picks “Picosats”

The smallest operational satellites ever flown—built by Aerospace with Defense Advanced Research Projects Agency (DARPA) funding—were selected by Popular Science as one of the top 100 technologies for the year 2000. About the size of cellphones, these picosatellites, or “picosats,” were featured in the magazine’s December 2000 issue in the “Best of What’s New” section.

Project director Ernest Robinson of the Aerospace Center for Microtechnology accepted an award for Aerospace at a Popular Science exhibition in New York in November 2000. A pair of these picosats flew a groundbreaking mission in February 2000 with the primary goal of demonstrating the use of miniature satellites in testing DARPA microelectromechanical systems (MEMS). Two more picosats, launched in July 2000, are scheduled for orbital release during the summer of 2001. (Winter 2000/2001)
Successful Launch of NRO Satellite

The National Reconnaissance Office (NRO) successfully launched its GeoLITE satellite from a Delta II rocket on May 18, 2001, from Cape Canaveral. This was the first time an NRO satellite was launched on a Delta II. Aerospace provided critical support throughout the launch campaign, from source selection to early-orbit operations.

The GeoLITE program broke from traditional NRO practices, said Tom Dorune of the Advanced Technology Group, moving instead toward a more streamlined acquisition of the spacecraft and a more commercial procurement toward a more streamlined acquisition of the Advanced Technology Group, moving instead models to simulate the flow of air around the WB-57F during flight.

Clouds are formed, dissipate, and affect the heat balance of the lower instruments carried by the WB-57F to study how high-altitude cirrus clouds, close high-altitude formation flying with the NASA ER-2, are sampled the shield cloud of this system on July 27, 2002. A key properties of the ice particles that make up the shield. The WB-57F extensively posed of ice crystals forming a high-altitude “shield” over the entire area. A key objective of CRYSTAL-FACE was to investigate the microphysical and radiative properties of the six particles that make up the shield. The WB-57F extensively sampled the shield cloud of this system on July 27, 2002.

More detailed results from CRYSTAL-FACE will be presented at the spring meeting of the American Geophysical Union in Nice, France. The continuing collaboration between the Air Force, NASA, and other agencies under the RISO program provides the Air Force with important credibility, as well as engagement with the atmospheric science community with regard to the impacts of aircraft and rocket-engine combustion emissions on the atmosphere. (Winter 2002/2003)

Aerospace Takes Part in NASA CRYSTAL-FACE Mission

The Aerospace Corporation played a key role in the recently completed airborne cloud sampling campaign of the Cirrus Regional Study of Tropical Antis and Cirrus Layers—Florida Area Cirrus Experiment (CRYSTAL-FACE).

The campaign was part of a continuing interagency effort to better understand the ways in which the atmosphere—system—composition emissions affect atmospheric chemistry and radiation. Sponsored by NASA, the CRYSTAL-FACE effort extends previous joint Air Force and NASA work under the Rocket Impacts on Stratospheric Ozone (RISO) program.

Preliminary analysis of the data has provided new insights into the size, shape, and chemical composition of cirrus and contrail ice crystals and how these clouds could affect global warming,” said Martin Ross, Aerospace RISO program manager. Ross served as co-flight scientist (with Randall Friedl of NASA’s Jet Propulsion Laboratory) for high-altitude aircraft WB-57F payload integration and operations during CRYSTAL-FACE deployment to Key West Naval Air Station, Florida, in the summer of 2002. He directed a team of more than 150 scientists and engineers operating 27 instruments carried by the WB-57F to study how high-altitude cirrus clouds are formed, dissipate, and affect the heat balance of the lower atmosphere.

William Engblom of Aerospace applied state-of-the-art computer models to simulate the flow of air around the WB-57F during flight in an effort to understand how aircraft-induced changes in air pressure and temperature could influence the response of instruments carried by the aircraft. Highlights of the month-long CRYSTAL-FACE mission included sampling a variety of thunderstorms-related cirrus clouds, close high-altitude formation flying with the NASA ER-2, and sampling of the WB-57F’s own contrail.

In the Spirit of Opportunity

NASA’s Jet Propulsion Laboratory (JPL) recently landed mobile scientific rovers called “rovers” on the surface of Mars. The first of the two rovers left Cape Canaveral aboard a Delta II rocket and safely touched down six months later on January 3, 2004. The second arrived three weeks later.

Aerospace was involved in this historical mission at varying levels since its beginning, roughly four years ago. “It is our first example of participation on a JPL project from inception to operation,” said Dave Bearden, Systems Director of Aerospace’s NASA/JPL Advanced Programs Office. Aerospace was part of a team supporting diverse areas, such as requirements management, general systems engineering, selected redundancy studies, risk management, mission visualization, subsystem peer reviews, launch vehicle mission planning, mission design and operations review, analysis of surface-to-orbit communication links, test anomaly resolution, and cost and schedule evaluations.

Aerospace’s Satellite Orbit Analysis Program, for example, played a role in the spacecraft trajectory design. “We ran visualizations that showed basically the launch and the travel to Mars and the entry, descent, and landing on to the surface,” said Bearden. Texture maps—representations of the geologic features on the planet—made the program even more useful in targeting certain landing areas.

Precision Window for the Space Station

When astronauts view Earth from the International Space Station, they will look through a glass porthole developed by Karen Scott of Aerospace. This 20-inch-diameter window provides a view of more than three-quarters of Earth’s surface and is the highest quality window ever installed in a crewed spacecraft. Astronauts will be performing long-term global monitoring with remote-sensing instruments and Earth science photographic observations.

As optical scientist for developing the window, Scott tested the viewing glass originally planned for the window and found that it would not support high-resolution telescopes or precision remote-sensing experiments. Her recommended upgrade was approved for the four-piece window, now consisting of a thin exterior “debris” pane, primary and secondary pressure panes, and an interior “scratch” pane.

Scott led a 30-member team from Johnson and Kennedy Space Centers, Marshall Space Flight Center, and the University of Arizona Remote Sensing Group that conducted calibration tests on the upgraded window before it was installed in the Destiny module scheduled for launch in January 2001. The team determined that the window could support a wide variety of research, including the monitoring of coral reefs and Earth’s upper atmosphere. Scott’s efforts in completing the tests on a tight schedule brought her a Johnson Space Center group achievement award. (Winter 2000/2001)
Lidar Calibrates Sensor on Orbit

The Defense Meteorological Satellite Program (DMSP) has a new tool for predicting weather that could affect ground combat operations. The Special Sensor Microwave Imager/Sounder (SSMI) is a multifrequency passive microwave sensor that is designed to enhance and extend DMSP microwave imaging and sounding capabilities. Aerospace played a key role in conceiving and developing the new instrument and is now verifying operation following launch of the first SSMIS on DMSP F-16. SSMIS aligns temperature and water-vapor readings within the same view of Earth and uses a conical scan, providing a constant angle of incidence at Earth’s surface. This is expected to increase resolution and accuracy of sounding information used in weather forecasting. Aerospace lidar measurements were recently used to confirm that key temperature and water-vapor channels are responding correctly and that calibration of most sounding channels is accurate.

“Aerospace is the only profiling method capable of meeting the accuracy and altitude range requirements needed to confirm SSMIS calibration accuracy,” said John Wessel, Distinguished Scientist in the Electronics and Photonics Laboratory. The lidar methods employed are based on Rayleigh and Raman scattering of light, he explained. In lidar, a laser emits optical pulses up into the atmosphere, and light that is scattered at Raman-shifted wavelengths, corresponding to vibrational frequencies of atmospheric constituents. Raman scattering can be used to measure water vapor in the troposphere when wavelength-selective elements are used to discriminate the water-vapor signal. Round-trip times are recorded for the signals, providing range profiles for temperature and water vapor. Radiative transfer calculations are performed on the lidar profiles, providing accurate simulations of radiances expected from the SSMIS microwave channels. These can then be compared to the actual profiles derived from SSMIS.

Robert Farley and Shaun Stoller deployed the Aerospace/DMSP lidar at Barking Sands, Kauai. Wessel analyzed the lidar data to produce atmospheric water-vapor and temperature profiles, and Ye Hong applied a custom radiative transfer code to these. This code converted the measured atmospheric profiles into the brightness temperatures that SSMIS was expected to observe during overpasses of the lidar site. The results agreed well with SSMIS brightness temperatures for most channels, although two channels were found to exhibit biases that may require revision of SSMIS calibration coefficients. A second campaign is underway, said Wessel, with a goal of improving measurement statistics and extending upper atmospheric temperature profiles over the range sensed by the highest altitude temperature channels of the new upper atmospheric sounding system.

Aerospace began developing lidar calibration facilities for heritage microwave sensors in 1993 and has performed sensor calibrations for five DMSP satellites. (Winter 2003-2004)

Beaming Power to Satellites

Batteries add mass, cost, and uncertainty to satellite missions—but such concerns may soon be a thing of the past. A recent study by Aerospace indicates that lasers can be used to beam power from an orbiting space structure to a constellation of satellites. What’s more, preliminary results show that with the expected advances in optical technologies, total system cost can be lower than that of traditional power systems.

The concept builds upon the Air Force Research Laboratory’s PowerSat, a large free-flying thin-film solar array. By adding solid-state lasers, thermal controllers, and optical telescopes to this platform, Aerospace researchers were able to create a satellite—the PowerSat—with optical power-beaming capability. Several architectural treatments were being investigated to determine the cost and performance advantages of each.

One model found that just two PowerSats could provide a full-time energy supply to a constellation of 12 low-Earth-orbit satellites.

In this configuration, each mission satellite keeps its existing solar array, battery and most of its power-management system. This arrangement substantially reduces the mass, volume, and cost of each satellite. Moreover, the power available to the mission satellites can be varied in real time, enabling better power optimization based on the requirements of the constellation payloads. (Summer 2001)

A Ringside Seat

After years of traveling through the lonely depths of space, the Cassini spacecraft finally reached its destination this summer, surviving a critical flyby into near-perfect orbit around Saturn on July 1. Since then, Cassini has been transmitting remarkable images of the planet’s rings and principal moon, Titan. The success of this mission, managed for NASA by Caltech’s Jet Propulsion Laboratory (JPL), has given scientists around the world a cause for celebration—including some at Aerospace, who provided technical support during various phases of the program.

For example, from approximately 1995 through launch in 1997, Aerospace, in partnership with Lincoln Laboratory, jointly conducted an independent readiness review of the satellite for NASA. James Gilchrist, Aerospace cochair of the review, said it encompassed the spacecraft design, most of the instruments built by U.S. manufacturers, and the Huygens probe (sponsored by the European Space Agency). Aerospace also conducted an independent review of the Cassini ground operations. The review lasted more than two years and began with an early independent assessment of the trajectory design, which included an Earth flyby. This trajectory held potential risk because the spacecraft carried just 1.6 kilograms of radioactive plutonium dioxide to power its thermal generators.

Aerospace mission specialists, such as David Strodder, senior project engineer in the Software Assurance and Applications Department, played an integral role in developing the risk assessment methodology to support the environmental assessment and launch approval process for the mission. Aerospace participated in launch readiness tests and the Titan IVB launch vehicle processing, and was instrumental in developing procedures to support the design, installation, and test of a modified Solid Rocket Motor Upgrade actuator.

Aerospace supported integration of the payload, including special acoustic tests, thermal analysis, electromagnetic compatibility analysis, loads analysis, targeting, and software testing for the first Centaur launched on a Titan IVB.

In 1998 and 1999, at the request of JPL, Aerospace implemented a number of software enhancements to its Satellite Orbit Analysis Program (SOAP) to model the Cassini mission, said David Strodder, senior project engineer in the Software Assurance and Applications Department. Aerospace developed Cassini solid models and trajectories in 2002 and rendered them to help visualize maneuvers and scientific observation opportunities. JPL used SOAP for visualization and analysis of the June 11 Phoebe flyby, and Cassini is using it to visualize pointing and camera fields of view.

Aerospace also supported in October 2003 a review of the Saturn orbit insertion, the climax of Cassini’s long journey and the crux of mission success. “These maneuvers were performed very efficiently,” Strodder said. “Aerospace may have sufficient propellant to conduct an extended mission beyond the planned four years,” said David Bearden, Aerospace Systems Director, Jet Propulsion Laboratory Program Office. “Aerospace supports JPL, on Cassini’s successful seven-year journey to Saturn and insertion into orbit, and looks forward to the tremendous scientific return during the coming years,” he said. (Summer 2004)

Black Box for Spacecraft

In an effort to pinpoint sites where space debris will land on Earth, the Aerospace Corporation’s Center for Orbital and Reentry Debris Studies (CORDS) is working with the Air Force Space and Missile Systems Center to develop a “black box” similar to the flight-data recorders found on commercial aircraft.

“Data obtained using a black box could provide clues as to how changes in materials and construction might prevent large pieces of space debris from hitting Earth’s surface,” said Bill Ailor, CORDS director.

Many spacecraft, or pieces of them, return to Earth. A black box that would survive reentry may one day give researchers information about changes in material temperatures and loads on spacecraft as they reenter the atmosphere. The box may also help determine the “footprint” or area of Earth’s surface where debris will fall.

Surviving pieces of varying sizes can be spread over hundreds of miles. Many factors, including atmospheric conditions and the dynamic characteristics of the objects, influence the footprint location. (Winter 2002/2003)
VISION AND INTEGRITY: 
Dr. Ivan A. Getting 
1912–2003

President, 
The Aerospace Corporation, 1960–1977

Steven R. Strom

T he Aerospace Corporation lost its founding president and one of its most ardent advocates when Dr. Ivan A. Getting died October 11, 2003. From the company’s founding in 1960 until his retirement in 1977, Getting’s name was virtually synonymous with Aerospace. A brilliant visionary, he contributed to the world in ways that extend far beyond the company. Just last year, he shared the prestigious Draper Prize for his contributions to the development of the Global Positioning System, now recognized as one of the greatest aids to navigation in centuries.

Getting’s accomplishments have been cited numerous times in the flood of obituaries that chronicled his life: the development during World War II of the SCR-584 radar tracking system, which intercepted German V-1 rockets fired at England and saved thousands of lives; his oversight of the production of transistors while serving as vice president of Raytheon, the first time this was done on a commercial basis; his contributions in 1956 to the Project Nobska study, which recommended the development of a submarine-based ballistic missile that ultimately became the Polaris; and major contributions to the Mercury and Gemini space programs during his first years as president of Aerospace. These are just a few of his outstanding achievements.

Nonetheless, Getting was most proud of the role he played in the formation of The Aerospace Corporation. In the company’s formative years, Getting, more than anyone else, established the culture of uncompromising excellence that still endures more than four decades later. Under Getting’s direction, Aerospace became a close and valued partner of the Air Force in the development of national security space systems. Max Weiss, who organized the Electronics Laboratory in 1961 and retired as Engineering Group Vice President in 1986, recalls that it was Getting’s “absolute dedication to the importance of laboratory research at Aerospace” that “made the company much more effective as a trusted advisor to the government.”

Getting took time to mentor the younger members of the Aerospace staff, and Weiss noted that his delight in doing so, combined with his “passion for excellence,” his good sense of humor, and his “vision and integrity,” helped “set the tone for Aerospace, which made it a pleasure to work there.”

In addition to his support for Aerospace’s technical and scientific operations, Getting was a strong advocate for continuing education in the development of the Aerospace workforce, and not just in science and mathematics. During his tenure as president of the IEEE in the late 1970s, Getting helped establish the organization’s History Center. He was, in his own words, “a strong supporter of the role that history has to play in any organization.” He was also a great admirer of Crosslink, and felt that the magazine played a vital role in explaining to the outside world the importance of Aerospace activities. Just three days before his death, he contributed to the article on the Dyna-Soar program that appears in this issue.

Getting’s innovative contributions extended to matters that most folks at Aerospace take for granted, including the design of the main corporate campus in El Segundo. Getting closely followed the planning of new facilities for Aerospace, which began in 1963, making sure that the buildings were well designed and well lit and the grounds nicely landscaped to “create an environment that would help to foster the creative thinking of Aerospace employees.” He often worked late into the night with the architects and designers to ensure that the Aerospace buildings would be conducive to the company’s overall mission.

Getting’s brilliant mind was active right up to the time of his death. George Paulikas, former executive vice president, remembers that “he had a seemingly unbounded curiosity in matters scientific and technical. I recall that talking to him about a technical subject in 1961, or 2001 for that matter, was an invitation to discover how much you really knew—like a graduate school oral exam!” Max Weiss ably summarized Getting’s long career and the qualities for which he will be remembered: “He was an extraordinary figure of the 20th century, a brilliant scientist and engineer, a great leader of men and women, a major force in the defense of our freedom during World War II and the Cold War, a dreamer of dreams who willed them into reality, and above all a wonderful human being.”
A New CEO for a New Era

Donna J. Born
(Reprinted from Crosslink, Summer 2001)

The Aerospace Corporation last year celebrated 40 years of successful contributions to the national space effort and aerospace space. Guiding the company into its next 40 years will be William F. Ballhaus Jr., the corporation’s new president and CEO. Ballhaus comes to Aerospace particularly suited to lead this corporation as it meets the challenges of national security space in the new millennium. He brings insight gained from extensive research and management experience in government and industry. Experience, Ballhaus believes, is his greatest asset: “Experience develops intuition and prepares leaders for the most important thing they do—make decisions and make them correctly and quickly.” He has published numerous influential articles on computational aerodynamics and related technology, served as director of NASA’s Ames Research Center, and oversaw the engineering and technology functions of the aerospace defense contractor Lockheed Martin. His many awards for research and management testify to the quality and importance of his work.

The new CEO assumes leadership of the organization at a time when the government is proposing major changes in the structure and administration of the nation’s space and defense programs. The new direction will have a direct impact on Aerospace, whose primary customers are the Air Force Space and Missile Systems Center, Air Force Space Command, and the National Reconnaissance Office (NRO). The proposed changes will create a more integrated national security space infrastructure that aligns the Air Force and NRO programs for best use of resources and clearer lines of authority and accountability. The challenge to Aerospace, according to Ballhaus, will be determining how the company can best serve the needs of these customers. “Aerospace will play a major role supporting national security space. We have very experienced people in key positions who really understand national security space and the capabilities that support it,” Ballhaus said. “Our job is to provide sound technical advice in systems development and acquisition support, launch certification, systems engineering, process implementation, and technology application. And I think we do all that very well. Continuously we need to improve our tools to enhance Aerospace in September 2000.”

Technology investment is one way the corporation provides better tools and better processes for helping customers, Ballhaus said. Some of the technology investments one can make to solve large matrix equations to determine the flow field variables, for example, velocity, pressure, turbulence, etc. Relaxation is a technique used to solve large matrix equations to determine the flow field variables, for example, velocity, pressure, turbulence, etc.

Crosslink Research Center, and oversaw the engineering and technology functions of the national security space infrastructure that aligns the Air Force and NRO programs for improved customer service. The HMAT (an experimental, uninhabited aircraft specifically designed for flight tests of high-maneuverability test concepts) to improve maneuverability. “One of the most important things with Ballhaus is the ability to analyze transonic flows about wings of a given shape and continue to take pleasure in sharing it with others. He once tried to explain to a curious passenger sitting beside him on an airplane a discussion about ground concepts in research and continues to study the concept of aerodynamics and to understand all of the systems they see a market. “Our market is the NRO, Air Force, and other defense customers. What do they need? What’s missing? How can the technology enhance their ability to perform their mission?” The codes that Ballhaus wrote were applied, for example, to the first Cray 2 supercomputers to model the complex flow fields about a wing design and optimize its performance prior to wind tunnel or flight tests. The codes provide information such as shock formations and other flow characteristics and phenomena that determine aerodynamic performance. “Basically with finite-difference methods, we divided the codes that Ballhaus wrote were applied, for example, to the first Cray 2 supercomputers to model the complex flow fields about a wing design and optimize its performance prior to wind tunnel or flight tests. The codes provide information such as shock formations and other flow characteristics and phenomena that determine aerodynamic performance. “Basically with finite-difference methods, we divided the flow field into small cells, literally millions, and wrote equations for each cell that expressed conservation of mass, momentum, and energy using variable-resolution techniques to solve the resulting large algebraic (matrix) equations. The codes provide information such as shock formations and other flow characteristics and phenomena that determine aerodynamic performance. “Basically with finite-difference methods, we divided the flow field into small cells, literally millions, and wrote equations for each cell that expressed conservation of mass, momentum, and energy using variable-resolution techniques to solve the resulting large algebraic (matrix) equations. 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Foresight and Commitment: 45 Years of Aerospace

Joe M. Straus

Aerospace has been involved in virtually every national security space mission since the beginning of the space era and remains a major partner in developing the nation’s next generation of launch vehicles and satellite programs.

The two trends led to what is now recognized as wishful thinking. Believing that more could be done for less, both government and industry made certain assumptions about how space systems, including launch systems, could be acquired. The government believed it could cut costs by shifting much of its role to the commercial sector. The theory was that these profit-driven systems-integration and technology companies could develop complex space systems efficiently and economically, with little government oversight, thereby saving the government billions of dollars. In essence, the government would assume more risk to reduce cost, but would manage that risk.

The intent was noble, but the execution was flawed. Five launch failures occurred in 1996 and 1999, including two commercial ventures and three national security missions. In each case, hundreds or thousands of people did everything that was expected of them, and yet something—be it a nicked wire or an erroneous software constant—slipped by unnoticed. Assets of roughly $10 billion were lost, along with the critical functionality that the military, civil, and commercial communities were expecting from the satellites.

Raising the Bar

In response to these failures, the government sponsored a Broad Area Review (BAR), which made a number of recommendations for launch program recovery. The most significant recommendation was that mission success, rather than cost and schedule, should be paramount. The BAR report noted that billions of dollars worth of national space assets were riding on inherently risky vehicles, and that a focus on budget could at best achieve only a minimal reduction in cost, but with a substantial increase in risk.

The BAR report also emphasized that systems engineering needed more discipline, along with greater government oversight and formal risk management. Finally, the report noted that thorough postflight analysis was needed, even on successful launches.

In 2001, the Commission to Assess United States National Security Space Management and Organization also recommended a number of changes in the organizational structure of national security space. As a result, the Air Force and National Reconnaissance Office (NRO) space programs were assigned to the Undersecretary of the Air Force, who took on the additional roles of Director of the NRO and Air Force Space Command. To serve as the Undersecretary, he was assisted by a new team of space acquisition and how it could be improved.

Imagery Architecture (FIA) programs recently sponsored a Broad Area Review (BAR), which emphasized on cost resulted from the budget squeeze of the 1990s, when the programs were initiated.

Second, unrealistic estimates led to unrealistic budgets and to programs that could not be successfully executed as designed. Cost estimates were typically minimized during the advocacy phase to fit constrained budgets.

Third, undisciplined definition and uncontrolled growth in system requirements increased cost and caused schedule delays. The space acquisition system lacked disciplined processes to control requirements. Trade-offs among cost, schedule, and risk were generally not supported by rigorous systems engineering, budget, and program management processes.

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Third, undisciplined definition and uncontrolled growth in system requirements increased cost and caused schedule delays. The space acquisition system lacked disciplined processes to control requirements. Trade-offs among cost, schedule, and risk were generally not supported by rigorous systems engineering, budget, and program management processes.
Fourth, the government’s ability to lead and manage the space acquisition process in the face of DSP competition. The acquisition reforms of the 1990s had marginalized the roles of government agencies and federally funded research and development centers, such as Aerospace. At the same time, program managers lost authority to execute effectively. The government experience base in program management and systems engineering—crucial, which substantially damaged its ability to be a smart buyer.

Last, industry had failed to implement proven management and engineering practices on some programs.

The observations and recommendations of the team have led to a renewed emphasis on systems engineering and a focus on mission success. Aerospace has been deeply involved in these efforts. For example, Aerospace was appointed to the 2004 Mission Assurance Improvement Task Force, which was sponsored by the SMC Chief Engineer and the NRO Deputy Director for Systems Engineering. The recommendations of this task force have already yielded improvements in software processes, systems engineering practices; test effectiveness and verification; data, materials, and processes; and specifications and standards. In fact, the task force has been instrumental in revising and reinvigorating military specifications and standards that apply to space programs.

With the shift away from the tenets of acquisition reform, Aerospace has taken on a new level of corporate accountability for mission success, for program executability, and for timely identification of problems and corrective action. These accountability improvements complement Aerospace’s traditional role in providing objective technical recommendations based on sound analysis and expertise and serving as a technical archive to document and share lessons learned across the national security space community.

The Road Ahead

Today, three factors predominate the government’s strategy for space acquisition.

1. The first is the fact that warfare and intelligence organizations designed for the relatively stable Cold War period are not fast enough or adaptable enough to deter or respond to the unexpected and fast-evolving threats. This is especially true in the area of space systems that provide a vital capability—that is, global information collection and dissemination—needed for national security in this new environment.

2. The second is the growing realization that space systems provide a vital capability—that is, global information collection and dissemination—needed for national security in this new environment.

3. The third is the recognition that existing military and intelligence services can be made more effective by giving more information to more people, when and where they need it.

The goal is to predict the actions of adversaries and to move faster and more effectively than they do. Space systems are one critical component of this new capability, and within the last five years, the government has set out to recapitalize and improve every space mission area. As a result, virtually every current satellite and launch system will be replaced and a new generation—and in some cases, even the new generation will be replaced by a "transformational system" that is already being planned.

For example, in the area of widespread military satellite communications, the Defense Satellite Communications System (DSCS) is being replaced by the Wideband Gapfiller program, which is nearing completion of its first spacecraft. A single Wideband Gapfiller spacecraft will have the capacity of the entire DSCS constellation. The last DSCS III spacecraft entered service in December 2003, joining 11 other DSCS satellites operating at that time. Aerospace was instrumental in helping to raise the throughput of the constellation during Operation Iraqi Freedom by 15 percent using special operational procedures. By some estimates, 60 percent of all communications traffic at the height of the war went through satellites, which underscores the importance of maximizing the use of existing communication satellites.

Secure military communications programs are undergoing similar changes. Four orbiting Milstar satellites achieved the desired network connectivity in January 2002 after substantially more than a decade of development. The successes of the final Milstar spacecraft was particularly important because an earlier Milstar spacecraft had been lost due to a malfunction during launch of the new satellite’s upper stage. Aerospace was instrumental in ensuring that this final spacecraft reached orbit safely in April 2003 after evaluating a number of issues, including the possibility of "pogo" oscillations, which can destroy or damage the spacecraft during launch. The Advanced EHF program, which is now in the manufacturing stage and which will begin launching spacecraft in the next few years, is also the result of such a transformation.

The Global Positioning System (GPS) is also transitioning to a new era of enhanced capabilities. Many of the original GPS satellites have lasted beyond their expected lifetime. These are now being replaced by the GPS IIR spacecraft. The 52nd GPS spacecraft was launched in November 2004 and brought the number of operational satellites to 30, the largest GPS constellation ever. The new GPS IIF follow-on program is in the manufacturing phase and will begin launching in 2007. Following that will be GPS III, which is currently in the requirements definition phase. Aerospace has been deeply involved in the system engineering and evolution of this complex program and has delivered the replenishment strategy currently being considered by the government.

In the missile warning area, the venerable Defense Support Program (DSP) is being replaced by SBIRS, which has mission experts have expanded to include missile defense, technical intelligence, and battle-space characterization. The penultimate DSP launch in February 2004 marked the last Air Force launch on a Titan IV and the last launch of the Inertial Upper Stage (IUS). The last DSP spacecraft will launch in late 2005 aboard the heavy-lift variant of the Evolved Expendable Launch Vehicle (EELV). This will be the first operational launch of the EELV Heavy, and it will carry one of the oldest spacecraft in the inventory. Aerospace developed operational methods to increase the life of the existing DSP constellation by two years to help with the transition to the new SBIRS program, which will not begin launching for several years to come.

Aerospace has also been involved in developing the new ground systems for SBIRS, which are far more complex than the serious DSP ground systems.

Conclusion

With so many programs in transition, the national security space community will be challenged to find the proper mix of existing and new programs to ensure consistent mission success. But Aerospace can look back on its 45 years of history to know that mission success in space programs clearly requires a uncompromising focus on quality. And looking forward to the next five (or 45) years, Aerospace will work to ensure that its government customers never lose that focus.
Notable Contributions

E ach year, Aerospace bestows a number of awards that encourage, commend, and reward significant contributions of individuals and project teams that go far beyond normal expectations. The Trustees’ Distinguished Achievement Award is the most prestigious of these awards, acknowledging work of the highest caliber as determined by a panel of judges representing all facets of the Aerospace professional community. Collectively, these awards present a window into the inner workings of Aerospace, providing insight into the sort of projects that are pursued and the sort of results that can be achieved. Here, then, are the past five winners of the Trustees’ Distinguished Achievement Award, describing in their own words their contributions to the national security space community.


Recipients of the Trustees’ Award are usually honored for a single, major event, project, or capability. My award was for multiple contributions considered collectively, so I will highlight only a few of them. These contributions derived from my primary responsibility, heading up the independent stability and control analysis (ISACA) effort on the current three generations of GPS spacecraft. This activity involves independent developing all spacecraft sensors, actuators, and vehicle dynamic models, combining them with attitude-control flight software, and simulating and testing all aspects of the spacecraft’s flight regime to assess performance and stability.

The program office decided to fund the ISACA effort for all future generations of GPS after several instances of instability on orbit with the first generation of GPS spacecraft. A major outcome of the ISACA effort is the development of a real-time hardware-in-the-loop simulation that operates with actual flight software executing on the actual or equivalent spacecraft computer. Currently, there are three of these simulators for the GPS Block II/I/A, Block II/I/RM, and Block IIF spacecraft. The development and use of these real-time simulators requires a team of specialists. Their work involves flight software validation and testing, software and hardware simulation interface design, redundancy management testing and development, and on-orbit anomaly support. I am fortunate to have the support of an extremely talented team that includes Rita Mostrrelli, Chul Kim, S. L. Chow, and Kamran Aslam.

The simulators have pinpointed a variety of problems. For example, I found an inertia instability involving the Block II/I/A spacecraft when one of the reaction wheels failed. The program office was warned, and when the condition later occurred on orbit, procedures we developed to correct the problem were successfully implemented. Two other spacecraft missions were extended because of contingency procedures developed by our team using the Block II/I/A simulator.

Testing the Block IIR spacecraft uncovered 58 flight software discrepancies and five specific control-systeminstabilities that the contrator to correct prior to launch. Four of these instabilities would not otherwise have been found until the spacecraft was on orbit, placing the mission at risk.

The high-fidelity dynamics of our Block IIR simulator enabled us to simulate the Earth-acquisition sequence while one of the secondary payload antennas was deployed. This was a procedural change necessitated by a thermal constraint. The contractor’s simulation was incapable of this complex maneuver. Thus far, a total of 75 software patches have been developed for GPS Block IIR. No patch is uploaded to the spacecraft until it has been independently reviewed and tested by our team using the simulator.

Our testing of the Block IIF spacecraft software found several problems related to eclipse control and a weakness in the yaw turning maneuver during the spacecraft’s operation in low sun elevation regions. These problems were brought to the attention of the contractor for resolution.

The spacecraft contractors strive to prove that their spacecraft control laws perform to expectations and are stable with adequate control margins. Our ISACA testing strives to discover weaknesses or inadequacies in their control laws. The interplay between these two philosophies produces an improved design that not only meets but exceeds expectations. Our real-time simulators are used for extensive testing prior to launch, for supporting launch activities, and for assisting anomaly investigations. They are also used to train the Aerospace and Air Force early orbit support teams.

The real-time simulation capabilities have provided the Aerospace and Air Force Program Offices an independent validation of the adequacy of these three GPS spacecraft’s control system designs prior to launch. They have supported investigation of numerous on-orbit anomalies, and in general contributed to a more robust spacecraft design for the GPS worldwide community. These achievements have enabled the ongoing constellation sustainment effort to make efficient use of the older on-orbit spacecraft that have been kept operating well beyond their design lives.

William Feess (2002)

My award was for the work I have performed in support of the navigation mission of the GPS program. This is a brief history of my association with the program and some of my work since I began working on GPS in 1970, when it was called Program 621B. I was a member of the core team that defined the initial GPS.

Flight tests at White Sands, using four ground transmitters, supported the signal structure and the aircraft navigation concepts, and in 1973 the program got the go-ahead for the satellite phase of the program. I supported the proposal evaluation for the ground and satellite phases. Atomic clocks are the heart of the GPS system, and during this period I analyzed their performance characteristics and the role they played in satellite orbit determination and prediction.

Problems were encountered in the early launches affecting the accuracy of the satellite orbit estimation and prediction. The first of these involved the management of the spacecraft momentum wheels. Initial design was to dump (despin) the momentum wheels and to evaluate new materials or processing changes during materials manufacture. Our capability to perform these tests has increased significantly in recent years and, in some cases, the results from these tests may be the only available data on the stability of a material for a particular satellite program.

The knowledge gained from flight experience and ground testing is the basis for evaluating the environmental stability of a spacecraft material. It allows us to identify poor selections of materials and to avoid materials that would have degraded in the intended application. That knowledge also allows us to recommend or confirm acceptable alternatives. Selection of acceptable materials is one of the factors that contribute to achieving mission success in national space programs.

Wayne Stuckey

A satellite operating in what is generally considered to be the vacuum of space might seem like a hostile environment, but it is actually a hostile environment for the materials on the exterior surfaces of a spacecraft. That is the opening sentence of an article authored by me and Michael Medishi for the Summer 2003 issue of Crosslink. It sums up our need to understand space environment and its impact on spacecraft materials, which was a primary focus in my work at Aerospace. The degradation of the materials on a satellite may shorten its useful lifetime in orbit, so it is obviously important to know which materials provide the best stability and durability.

Our knowledge of the stability of spacecraft materials comes from experience with previously launched satellites and from testing programs. In some cases, we have been able to study materials returned from space. The space shuttle, for example, allowed us to study materials with our colleagues at NASA and in industry in several ways. Early shuttle flights revealed the importance of atomic oxygen reactions in the low Earth environment; that awareness led to experiments on materials in the shuttle bay during some missions. The shuttle also allowed the deployment of the Long Duration Exposure Facility (LDEF) in a low Earth orbit and its retrieval nearly six years later. Extremely useful data were obtained for thousands of materials in that environment. No materials have ever been returned from the higher orbits, but we often obtain flight data from those orbits that we can use to learn about material stability. It’s hoped that future opportunities will return samples to Earth from higher orbits.

These investigations have also provided a check on the ground-based testing that is conducted on the basis of knowledge of spacecraft materials. Although we have data on the performance of materials in low Earth orbit, we must rely on ground testing to know about materials in higher orbits.

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The first Block IIR (replacement for the aging Block II satellites) satellite de- 
scrubbed and started its mission initial timer. As with the Delta II, Atlas II, and 
Titan II vehicles, robust fault protection during launch was needed to ensure the 
military utility of proposed space systems. Further details about staffing needs and 
requirements can be found at http://www.aero.org/jobs/
Launch failures have been a fact of life for most space-faring nations since the space age began in 1957. Because a space mission involving a launch vehicle and a sophisticated satellite can easily cost hundreds of millions of dollars, investigation into why launches fail can provide valuable information for improving vehicle systems and cost savings. Any lessons learned from past experiences that could serve to mitigate launch failures in the future would make such an investigation extremely worthwhile.

A space launch failure is an unsuccessful attempt to place a payload into its intended orbit. This definition includes all catastrophic launch mishaps involving launch vehicle destruction or explosion, significant reduction in payload service life, and extensive effort or substantial cost for mission recovery. It also includes the failure of the upper stage of a launch vehicle, up to and including spacecraft separation on orbit. However, this definition does not include the failure of an upper stage released from the U.S. space shuttle. The U.S. space shuttle is both a launch vehicle and a space vehicle. An upper stage released from the space shuttle in orbit is considered a transfer vehicle, not a launch vehicle.

The space age began with the USSR launch of the first artificial satellite, a liquid-fueled Sputnik (SL-1), on October 4, 1957. At present, nine countries or consortia—the United States, the Commonwealth of Independent States (CIS, formerly USSR), European consortia, China, Japan, India, Israel, Brazil, and North Korea—possess space launch systems, demonstrate space launch capability, or conduct space launch operations.

Many current major space launch systems are based on early ballistic-missile technology, which regarded launch costs and schedules a higher priority than launch quality and reliability. The design of these space launch systems left much room for improvement, as demonstrated by launch failures of the past.

Financially, much is at stake in any kind of space launch. A small launch vehicle, such as the U.S. Pegasus, costs about $15 million, but a versatile, reusable launch vehicle, such as the U.S. space shuttle, costs well over $1 billion. A small experimental satellite can be purchased for a few million dollars, but an advanced spy satellite or scientific satellite may cost more than $1 billion. Furthermore, the possible monetary loss calculated for a launch failure does not include the expense, time, and effort spent during the recovery period or the cost of the damage to national prestige. Analysis of space launch failures is critical to a national space program’s future success.

A systematic look at worldwide launch successes as well as failures, including scrutiny of various launch vehicle subsystems, can shed light on precise areas that might be at the root of many problems. This type of study can also help suggest what actions to take to address those problems.
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Worldwide Space Launches

To understand space launch reliability, it is helpful to examine the history of launches worldwide since 1957. The successes made in space science and engineering during this period has been truly remarkable, as illustrated by the achievements of the United States and the CIS/USSR, the nations that have dominated the space launch arena.

To get an idea of how great that progress is, consider that in 1961, Sputnik 1 weighed only 83.6 kilograms, and on July 16, 1969, the U.S.'s Saturn V, the largest and most powerful operational rocket ever built, lofted Apollo 11, with a mass of 43,811 kilograms, to lunar orbit during the moon-landing mission. Today, the U.S. Space Transportation System routinely launches the shuttle orbiter, weighing more than 110,000 kilograms, to low Earth orbit. The orbiter flies like a spacecraft and lands like a glider.

The U.S.SSR was the first country to place a satellite carrying a person into Earth orbit. Its Soyuz vehicle has been statistically shown to be the most reliable expendable launch vehicle in the world. Since 1957, the CIS/USSR has carried out more space launches than all other countries combined. Between 1957 and 1964, 4704 space launches were conducted worldwide, including 2009 CIS/USSR launches and 1422 U.S. launches.

These figures include launches carried out individually by France and the United Kingdom (U.K.) over 30 years ago. France was the third country (after the CIS/USSR and the United States) to attain space launch capability, with its launching of a satellite in orbit in 1965. The U.K. developed a small vehicle, Black Arrow, which was launched successfully in 1971.

Currently, France and the U.K. participate through the European Space Agency (ESA) in the development of the Ariane launch systems. (The ESA is composed of 16 European nations.) The Ariane vehicles are launched through the European Space Agency (ESA), after several launch and satellite-on-orbit failures. The Japanese H-I/A and Mu-5 vehicles use state-of-the-art technology and represent the Japanese government's commitment to becoming a major player in space.

The remaining nations whose launches have been tracked have, for the most part, conducted space programs for very brief time periods. They have experienced mixed success records. India, undaunted by a series of early technical setbacks and launch failures in its fledging space program, allocates a significant portion of its yearly budget to space technology development. Since 1998 India has had a streak of successful consecutive space launches. And it has acquired GEO launch capability with the new GSLV vehicle. Israel's Space Agency launched its first satellite with the Shavit launch system on September 19, 1988. Its third satellite, launched April 5, 1995, contains surveillance equipment designed to provide reconnaissance and military observation. For national defense needs, Israel continues its active role in space launches, despite the failures in 1998 and in 2004.

In Japan, the National Space Development Agency (NASDA), National Aerospace Laboratory (NAL), and the Institute for Space and Astronautical Science (ISAS) were responsible for space research and development. Japan had an 18-year streak (1977-1994) of successful consecutive space launches. In October 2003, NASDA, NAL, and ISAS were merged into one single independent institution, Japan Aerospace Exploration Agency (JAXA), after several launch and satellite-on-orbit failures. The Japanese H-I/A and Mu-5 vehicles use state-of-the-art technology and represent the Japanese government's commitment to becoming a major player in space.

The following chart is a brief history of rocketry. It is also worth noting that since the end of the Cold War, national boundaries in the space launch business have become less distinct. Companies throughout the world have been marketing CIS/USSR launch vehicles for commercial launch service. Proton by Lockheed Martin/NASA is the Soyuz (October 1993, September 1994, through December 26, 1991), ballistic-missile buildup and the space race fostered the launches failed (the success rate was 91.4 percent), with an associated loss or signifi-cant impact on service life of 484 satellites (some launches included multiple payloads). A brief look at some of the most publicized, operations as early as 1865), and signal and illumination devices. The basics of rocketry have not changed: ignited fuel burns in a combustion chamber, and the resulting gases are forcefully expelled through a nozzle, propelling the rocket in the opposite direction. Until the first quarter of the 20th century, all rockets were developed using solid propellant. Today's space systems employ both solid-propellant motors and liquid-rocket engines to deliver payloads into orbit.

Original rocket technology did not progress much until the early 19th century, when Colonel William Congrave of England developed a fireservice bomb-carrying solid rockets. Long sticks trailed from his rockets to provide stability. Soldiers used Congrave's rockets during the British bombardment of Baltimore in 1814 at Watertown in the war with Napoleon in 1815, and in the Opium War with China in 1842 (Bombardment of Macao). The famous "rockets" Congress' "arsenal of death" ning Montal in the Battle of Rung-Fung. Besides military weapons, other applications for rockets over the years include fireworks, lifesaving devices (as early as 1882), whaling

<table>
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<th>Country</th>
<th>Success Rate (percent)</th>
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The number of successful and failed launches for the space-faring nations of the world between 1957 and 2004. The CIS/USSR has carried out more launches than all other countries combined.

<table>
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<tr>
<th>Country</th>
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Each space-faring nation's launch success rate as a percentage of its total launches.

In 1926, Goddard built a successful rocket using liquid propellant (gasoline as fuel and liquid oxygen as oxidizer). Germans used his 1939 design of a liquid rocket to build and test the first full-scale ballistic missile, Vergeltungswaffe-2 (V-2, "Weapon of Retribution"). In 1942, all modern liquid rockets can be traced to the V-2. With a mixture of ethyl alcohol as fuel and liquid oxygen as oxidizer, it could travel 320 kilometers. The V-2 carried warheads from the European continent to England in the "Siege of London" during World War II. At the end of the war, Russia captured V-2 manufac-
## Launch Successes (s) and Failures (f), 1957–2004

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## U.S. Launch Vehicle Successes (s) and Failures (f), 1957–2004

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*Note: India's first launch was on April 13, 1957, and France's first launch was on June 28, 1958.*

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*Source: Crosslink Spring 2005*
critical launch failures around the world will highlight the nature of system failures.

In the United States, 165 space launches failed, with an associated loss or significantly reduced service life of more than 200 satellites. Most of the U.S. space launches failed (101 out of the 165 occurred during the first 10 years of space exploration (1957–1966). In that period, the United States was diligently attempting to catch up to the USSR, which had gained an early lead in space exploration. The first space launch failure involved a U.S. Vanguard vehicle, which exploded two seconds after liftoff on December 6, 1957. The failure, which attracted tremendous public attention and criticism in the wake of two successful U.S. Spatnik flights, was the result of a low fuel tank and low injector pressure that allowed the high-pressure chamber gas to enter the fuel system through the fuel-injector head. A fire started in the fuel injector, destroying the injector and causing a complete loss of thrust immediately following liftoff.

The U.S. Saturn V had a single failure in the Apollo 6 mission on April 4, 1968, when the third-stage engine failed to restart because of fuel-injector burnthrough. The versatile Space Transportation System also suffered a single launch failure on January 28, 1986, when the Challenger, carrying a seven-member crew, exploded 73 seconds into flight. The launch management had waived the temperature-dependent launch commit criteria and launched the vehicle at a colder temperature than experience indicated was prudent. At such a low temperature, the rubber O-rings in the motor case joint lost their resiliency, and the combustion flame leaked through the O-rings and case joint, causing the vehicle to explode. The newly developed U.S. commercial launch systems, including Delta III, Conestoga, Athena, and Pegasus, suffered launch failures during their early developmental flights, a repeat of Vanguard, Juno, Thor, and Atlas failures in the late 1950s and early 1960s. In January 2003, the orbiter Columbia, carrying a seven-member crew, exploded on its return-to-Earth flight. But the catastrophic event is considered a spacecraft failure and not a launch failure. CイスUSSR experienced an impressive number of space launches and a strong launch success rate in the past. However, the number of space launches and the success rate in recent years have declined, mainly because of domestic financial problems. From 1996 to 1999, for example, the United States conducted more space launches than CイスUSSR for the first time in 30 years. In 2000–2004, there were six failures with CイスUSSR launch vehicles, compared to one failure with the U.S. launchers.

Space launch failure in a closed society like the USSR or the People’s Republic of China was guarded as a state secret and not publicized in news media. Recently, though, because of “glasnost” in Russia, commercial competition, and requirements by the launch service insurance company, information flow on space activities has improved dramatically. Since the collapse of the USSR on December 26, 1991, Cイス has released information on many USSR space launch vehicles that were not previously known to the West. Making this information accessible has provided a much more complete picture of worldwide space launches, although the vast amount of information existing in CイスUSSR from both successful and failed launch operations is yet to be assimilated by space launch communities of the world.

One CイスUSSR space launch failure involved an SL-12 Proton vehicle carrying a Mars-96 spacecraft on November 16, 1997. The second stage of the Proton’s fourth stage did not take place, and the spacecraft did not reach the interplanetary trajectory. It reentered Earth’s atmosphere over the South Pacific Ocean. For lack of funds, Cイス launched this spacecraft without conducting a prelaunch systems checkout at the launch site. Some of the mechanical integration of the spacecraft and launcher was carried out by the light of a kerosene lantern (electrical power had been cut off because of unpaid bills). Tight funding also made ground control difficult, even during the critical period immediately following launch. The spacecraft itself commanded the fourth-stage release, indicating that it had possibly sent incorrect commands. It took 10 years to completely the $300 million Mars-96 spacecraft carrying two dozen instruments supplied by 22 countries. This launch failure halted plans for gathering valuable data about the planet Mars.

The failures of the European Launcher Development Organization (ELDO) Europa vehicle were reminiscent of the early launch failures in the U.S. space program (ELDO was one of the predecessors of ESA.) After terminating the Europa program, Europe spent many years planning the Ariane launch systems, which have experienced 10 failures since 1980. A recent failure involved a new Ariane-5 vehicle, the most powerful in the Ariane family. During its maiden flight on June 4, 1996, it veered off its flight path and exploded at an altitude of 3700 meters only 40 seconds after liftoff. The failure was attributed to errors in the design and testing of the flight software. The flight software was programmed for Ariane-4 launch conditions, but it was never tested in conditions that simulated Ariane-5’s trajectory. The more powerful Ariane-5 travels at a much faster horizontal velocity than the Ariane-4. Significant horizontal drift caused an overflow error in the inertial reference system (IRS) software, halted the primary and backup IRS processors, and resulted in the total loss of accurate flight guidance information.

From 1991 to 1996, the Chinese space launch record was marred by five failures. The most catastrophic failure occurred during the launch of a CZ-3B vehicle carrying a commercial satellite, Intelsat 708, on February 14, 1996. The 55-meter-tall CZ-3B is China’s most advanced vehicle. On its maiden flight, the CZ-3B began to veer off course two seconds after liftoff, before it even cleared the tower at the Xichang launch site. The vehicle and its payload hit the ground and exploded in an inhabited area near the launch site 22 seconds after liftoff. The explosion demolished a village and a nearby military base, and caused severe casualties and property damage.

The cause of failure was traced to the CZ-3B’s guidance and control subsystem. A gold-aluminum solder joint in the output of one of the gyro servo loops failed, cutting electrical current output from the power module and causing the inertial platform of the vehicle’s guidance and control system to slope. This caused computers to send the vehicle veering off the planned trajectory shortly after liftoff. The failed module was the only one of six similar modules that lacked conductive adhesive to reinforce the solder joint.

The Japanese liquid-propellant rocket, H-Ⅱ, suffered two launch failures during 1998 and 1999, and the upgraded H-ⅡA suffered one launch failure in 2003. Japan’s other eight launch vehicles (including four Lambda-4S failures during the period 1966–1969) involved solid-propellant rockets. One of the failures occurred on January 15, 1995, during the last flight of the Mu-Ⅲ-SⅡ vehicle. At 103 seconds after launch, the vector control thrusters, which partly control the rocket’s pitch, began to oscillate. The rocket veered off course 140 seconds after liftoff. The payload of the Mu-Ⅲ-SⅡ, a German satellite (Express 1), was put in the wrong orbit of 120 kilometers altitude, instead of the intended orbit of 210 kilometers altitude. The launch of the satellite, which fell into a jumble in Ghana after circling Earth two and a half times, failed because of improper modeling of the flight control dynamics relative to the weight of the payload. (Prior to the failure, the heaviest payload carried by the Mu-Ⅲ-SⅡ had been 430 kilograms, Express 1 weighed 748 kilograms.) Extra propellant had been added to the three stages and to the kick motor of the vehicle to provide extra thrust for the flight of the Express 1 satellite.

The flight was the eighth and final mission of the Mu-Ⅲ-SⅡ vehicle.

Several satellites have plunged into Bengal Bay since India’s space program began in 1979. India’s Polar Satellite Launch Vehicle (PSLV) is designed to place payloads into a polar sun-synchronous Earth orbit. On its maiden flight on September 20, 1992, the
PSLV experienced an unplanned change in pitch when the spent second stage separated from the vehicle at 134 seconds into flight. The third and fourth stages ignited normally, but the vehicle was unable to recover from the pitch change and did not reach sufficient altitude. The payload was placed in a 349-kilometer orbit instead of the planned 814-kilometer polar orbit. Shifting liquid fuel in the second stage of the vehicle may have caused the change in the vehicle’s pitch. Malfunction of the vehicle’s guidance system or failure of the control system to respond properly to the course deviation could have been the cause of the failure.

Causes of Failure
Available launch-failure data reveal much about patterns in the possible causes of failure. Many failure causes fall into the category of human error—either judgment or, launch-management decisions. Others are the result of defective parts. Failure can have its root in any phase of launch vehicle development—difficulties have been noted in inadequate designs and component tests; in improper handling in manufacturing and repair processes; and in insufficient pre-launch checkouts. Many past failures could have been prevented if rigorous reliability-enhancement measures had been taken.

Launch vehicle failures are usually attributed to problems associated with a subsystem, such as propulsion, avionics, separation/staging, electrical, or structures. In some cases the failure is ascribed to problems in another area altogether (e.g., launchpad, ground power umbilical, ground flight control, lightning strike) or to unknown causes (usually when subsystem failure information is not available).

Launch vehicle failures between 1980 and 2004 have been investigated, and launch failure causes in the United States have been found to include fuel leaks (resulting from welding defects, tank and feedline damage, etc.); payloads separation failures (from incorrect wiring, defective switches, etc.); engine failure (the result of insufficient braising in the combustion chamber), and loss of vehicle control (because of lightning, damaged wires that caused shorted, and control-system design deficiencies). In Europe and China, launch failure causes during the same period included engine failure (from combustion instability, hydrogen injector valve leakage, clogged fuel lines, etc.), short circuits, engine thrust loss, software design errors that resulted in guidance system failure, wind shear, and residual propellants.

Statistics show that among the causes of failure for space launch vehicles worldwide from 1980 to 2004, propulsion subsystem problems predominated. That particular subsystem appears to be the Achilles’ heel of launch vehicles. Sixteen of the 31 U.S. failures were failures of the propulsion subsystem. The unknown failures in the CIS/ USSR could include many in the propulsion subsystem.

The propulsion subsystem, the heaviest and largest subsystem of a launch vehicle, consists of components that produce, direct, or control thrust. Depending on launch vehicle position or attitude. Its many elements include main propulsion components of rocket motors, liquid engines, and thrusters; combustion chamber; nozzle; propellant (both solid and liquid); propellant storage; thrust vector actuator and gimbal mechanism; fuel and propulsion control components; feed lines; control valves; turbopumps; igniters; motor and engine insulation. Similar components are also used as separation mechanisms in the separation/staging subsystem.

Propulsion subsystem failures can be divided into failures in solid-rocket motors and liquid-rocket engines. Solid-propellant launch systems include Taurus, Conestoga, Athena, Minotaur, Pegasus, and Scout. Liquid-propellant launch systems include Titan II, Titan IIA, Titan III, Atlas, Atlas IAS, V, 4x, 5x, Delta DM-9, A, B, and C, and Delta IV M, IV H. Hybrid launch systems, consisting of liquid-propellant and solid-propellant rockets, include STS, all other Titan, Atlas, and Delta. The success rate of the propulsion subsystem in the United States from 1980 to 2004 was 98.6 percent for solid rocket motors and 97.9 percent for liquid rocket engines.

Addressing the Propulsion Problem
Solid-rocket motors and liquid-rocket engines of the propulsion and separation/staging subsystems both require sets of precautionary measures to maximize reliability and safeguard against failure. First, consider solid-rocket motors. In the design phase, to reduce risk it is important to apply current analysis techniques to ensure fast, accurate, and low-cost modeling of precise configurations prior to hardware fabrication.

In the construction of solid rocket motors, a number of safeguards apply to the preparation of solid propellant:

• Upon receipt from the supplier and prior to use, the propellant ingredient should be checked to ensure that it meets

Solid and Liquid Rockets
Whether or not they know it as Newton’s Third Law, most people have probably heard the statement “For every action there is an equal and opposite reaction.” That expression is the principle behind rocketry. The action is the expulsion of gas through an opening; the reaction is the rocket’s thrust. It’s not unlike what happens when you blow into a balloon, then release it. As air escapes (that’s the action), it propels the balloon (that’s the reaction), making the balloon zip through the room until it is completely gone.

In order to create a forcible expulsion of gas from a rocket’s fuel in a combustion chamber is ignited. The fuel can be in the form of solid or liquid substances; some rockets (“hybrid launch systems”) may make use of both. These substances are the propellants that characterize rockets as either “solid-rocket motors” or “liquid-rocket engines.” For the fuel to burn, oxygen or another oxidizing substance must be present. When the fuel burns, gases accumulate and pressure builds until the gases are expelled through an exhaust nozzle.

In solid-rocket motors, the fuel and oxidizing chemicals are suspended in a solid binder. Solid motors are used as boosters for launch vehicles (such as the space shuttle and the Delta series). They’re very reliable, and they’re simpler than liquid engines, but they’re difficult to control. Once a solid rocket is ignited, all its fuel will be consumed, without any option for adjusting thrust (force).

Liquid-rocket engines are more powerful than solid-rockets motors—they can generate more thrust—but the price of their power is complexity, in the form of many pipes, pumps, valves, gauges, and other parts. Liquid rockets require attention to storage issues and oftentimes the need to maintain very cold temperatures. Their complexity affects vehicle reliability, if only because the introduction of more components means the introduction of more opportunities for problems to occur.
specifications, and the propellant mix procedure and burn rate should be checked for every mix before casting.

Motors should be cast from a single lot of material to minimize thrust imbalance of vehicles with multiple solid rocket motors.

Solid propellant should be cast in a vacuum, if possible, to reduce the number and size of internal voids.

Modern techniques (e.g., computer tomography technology) are used to detect solid-propellant defects and propellant-to-insulation bondline separation before motor assembly.

Still other steps can be taken to help increase the likelihood of solid-rocket motor launch success. Chemical fingerprinting can be implemented for rare and sensitive chemicals such as propellant binder, motor case resins, flexseal elastomers, and adhesives. It should be possible to schedule into the development and qualification programs a motor-case cure study wherein a cured case is dissected to assess the adequacy of the process used in case-manufacturing.

The liquid-rocket engines of propulsion and separation/staging subsystems should be designed and built with robustness and with high thermal performances, structural margins to allow for manufacturing deviations. Welded joints instead of seams ought to be used for fluid lines, high-pressure equipment must be allowed in tanks, hydraulic lines, and plumbing; and 100 percent inspection, rather than spot-checking, must be applied to all welds.

Other preventive measures for liquid engines include the application of redundancy in fluid valves and igniters; the utilization of effective liquid film cooling or ceramic coatings to increase thrust-chamber durability; and the application of advanced high-strength (aluminum-magnesium) welding and milling for the construction of thin-walled fuel and oxidizer tanks. Helium purging (for cryogenic propellants) or nitrogen purging (for storable propellants) of oxidizer/fuel pumps and pipelines needs to be done before engine start-up, and purging of the chamber cooling duct should be done at engine shutdown, to provide a clean flow duct and to avoid the danger of fire or explosion.

Testing liquid engines is also important. They should be qualified at above the maximum operating environment, conditions, and duration. And extensive tests on engine operation should be conducted under various conditions after transportation of the engine, since transporting an engine subject is to a harsh environment that can alter its operation.

Enhancing Launch Reliability

Information gathered from failure studies of past launch vehicles indicates that following certain work practices could greatly enhance the reliability of launch vehicle systems. Of primary importance is the need to review and implement all lessons learned from past failure studies to avoid future reocurrences. It is necessary to incorporate preventive measures in all aspects of system development—design, building, testing, and operations. Launch vehicles should be designed for low cost in manufacturing, operations, materials, and processes rather than for maximum performance or minimum weight. Comprehensive design analyses should be conducted, with positive margins.

In the manufacturing phase, only flight-proven and defect-free components should be used. Advanced electronic beam welding, automation, and robotics should be applied for producing component manufacture. Stringent control of raw materials, components, and semifinished products ought to be practiced. Multistrand/redundant аrioceramics, electric, and ordnance components should be implemented for fault tolerance. Pyro-shock loads ought to be reduced whenever possible. Testing is a critical area for reliability enhancement. It is important for a design to be validated by testing components to the point of destruction or with a high enough margin to allow for manufacturing and operating environment variaces, like the successful design margin testing performed on ballistic missiles. Electrical and pneumatic connection tests should be performed for each stage and between the stages before vehicle assembly.

Components, software, and system-level electrical elements need to be tested under conditions that simulate an actual launch; system performance and flight simulation tests should be conducted; the results of testing during the development phase should be analyzed, and measures taken to improve product reliability. The separation mechanism function should be confirmed with a full-size dummy booster in its actual work environment should be minimized, and inspection testing should be tailored for specific works.

When the system is operational, it is important to limit space launch operation to the design environment and flight experience. Prelaunch procedures and launch processes should be simplified to reduce time consumption and damage in handling and processing. Launch-management training needs to be improved where possible. Final technical risks associated with schedule-driven launch dates should be reduced.

Conclusion

The technologies that have been developed for space applications and their spin-offs have dramatically improved human life, and they will no doubt continue to do so. Global high-speed telecommunication, videconferencing, and Internet applications require many satellites, which means the need for launch services will continue to grow.

In times of conflict as well as peacetime, space technology is of critical importance to the nation. Just as, more than half a century ago, the air advantage of the Allied Forces contributed significantly to the cause of World War II, so in the future, space technology will have the ability to influence conflicts. The Falkland Islands War of 1982, the Persian Gulf War of 1990, the war on terrorism in Afghanistan in 2001, and the war on totalitarianism in Iraq in 2003 are examples of how the intelligent utilization of space resources affects outcome.

In coming years, needs for commercial and national defense space-related technologies are expected to multiply in many areas: propulsion, guidance and control, communications, navigation, tracking and data relay, weather forecast, remote sensing, surveillance, laser weapon systems, missile defense, and interplanetary exploration. The demand for space launch services is ever increasing and may soon exceed the U.S. government’s defense budget.

As more launches are conducted, more possibilities for failure will present themselves. The increasing reliability launch systems will be ongoing. It is clear that any lessons learned from past failures are worth judiciously implementing if doing so can prevent future ones.

Further Reading


Optimizing Performance Through Constellation Management

Paul Massatt and Wayne Brady

Deciding where to put the GPS satellites is no easy task. Research at Aerospace has been instrumental in answering the fundamental questions of constellation management: how many, how high, how close, and how long.

(Previously published in Crosslink, Summer 2002)

The configuration of the Global Positioning System (GPS) has always represented a compromise between user needs, technology, and technical feasibility. The constellation has evolved to reflect changing requirements and program support, but the overriding management goal has never wavered: provide the most functional system for the broadest class of users, given a limited amount of resources. In pursuit of this goal, the GPS community must continually ask where to place satellites to best meet current and future needs. Research at The Aerospace Corporation has been influential in helping to answer that question.

Initial Proposals

The 24 primary satellites in the GPS constellation orbit Earth at an altitude of roughly 20,000 kilometers, circling the planet twice a day with precisely repeating ground tracks. Each of the six orbital planes, inclined 55 degrees relative to the equator and evenly spaced around Earth, contains at least four satellites, and some contain an additional spare satellite.

A 24-satellite baseline constellation was first proposed in the late 1970s. Various studies indicated that a three-plane constellation could provide greater coverage than a uniform three-plane constellation.

Consequently, the decision was made to switch from shuttle launches to Delta booster launches, and this
switch caused a three-year delay in launching Block II satellites. Shortly after the Challenger explosion, one of the Block I satellites failed. The Air Force was concerned that another satellite—the oldest on orbit—might also fail, eliminating any testing coverage of a day-long constellation on point-by-point evaluation over an extensive space-time grid. In addition, GPS receivers only locked onto four satellites at a time, so every combination of four satellites had to be examined individually. This method was cumbersome and slow. To optimize performance, one had to evaluate coverage over the large grid while also trying to determine how much to move the satellites, methodically repositioning each one and assessing its impact on performance. Moreover, the procedures required multiple iterations.

Researchers quickly realized that an optimum could not be achieved through traditional point-by-point grid evaluations. A breakthrough came when they applied new analytical methods using newly improved software. These changes considerably increased the efficiency of each objective function evaluation. They also allowed researchers to compute the effect of changing satellite locations more quickly. Rather than look at the effect of moving the satellites one at a time, they could track the satellites involved at the start and end of each period of degraded accuracy and analyze the effect of changing just those satellites. With these software efficiencies in place, optimization became much more feasible.

Spares and Pairs

While the GPS program office was transitioning to the initial 18-satellite target, Aerospace performed optimization studies to determine whether the planned spares could be integrated more fully into the overall design to provide global coverage. Researchers began by studying the nature of the bands of degraded accuracy experienced with the 18-satellite, six-plane uniform constellation. Analysis showed that the degraded accuracy was produced at locations and times when only four satellites were visible. Moreover, it appeared that the high degree of symmetry inherent in the uniform constellation was not a factor in this problem. By carefully characterizing all of the regions of degraded accuracy, Aerospace determined that nonuniform fivefold coverage could be provided over the affected regions by substituting three satellites with three spares and pairs of satellites. A small movement of two additional satellites enabled the constellation to be optimized, but finding an existing one, meaning it would perform better in case any satellites unexpectedly failed. Raising the inclination angle to 60 degrees or more, the inclination was preserved at 55 degrees. The Air Force approved the 21-satellite constellation as the new baseline and instructed the GPS Joint Program Office to implement it as soon as possible.

While this strategy would prevent complete outages, it did not improve accuracy as much as desired; in fact, several regions would still experience substandard performance. Hence, Aerospace began searching for a way to optimize local performance. Several obvious cases had to be overcome before an optimization algorithm could be developed. For example, the methods generally used to evaluate coverage over the whole Earth throughout the course of a day-long constellation on point-by-point evaluation over an extensive space-time grid. In addition, GPS receivers only locked onto four satellites at a time, so every combination of four satellites had to be examined individually. This method was cumbersome and slow. To optimize performance, one had to evaluate coverage over the large grid while also trying to determine how much to move the satellites, methodically repositioning each one and assessing its impact on performance. Moreover, the procedures required multiple iterations.

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Gearing Up

The Aerospace analysis generated a nonuniform 21-satellite, six-plane constellation that had practically no degraded accuracy or worse drops in performance. The new constellation was also deemed more robust than the existing one, meaning it would perform better in case any satellites unexpectedly failed. Raising the inclination angle to 60 degrees or more provided over the affected regions by substituting three satellites with three pairs of satellites. A small movement of two additional satellites enabled the constellation to be optimized, but finding an existing one, meaning it would perform better in case any satellites unexpectedly failed. Raising the inclination angle to 60 degrees or more, the inclination was preserved at 55 degrees. The Air Force approved the 21-satellite constellation as the new baseline and instructed the GPS Joint Program Office to implement it as soon as possible.

The coverage provided by the GPS constellation has grown more robust over time. These color contour plots show the cumulative amount of time per day that portions of the globe experience degraded accuracy (i.e., position error exceeding 9 meters or so). The first plot (top left) shows the amount of degraded accuracy for the full 21-satellite nonuniform constellation. The second plot (top right) shows that very few areas of degraded accuracy remain for the full 21-satellite nonuniform constellation. The third plot (middle left) shows that the 21-satellite constellation is sensitive to a single satellite failure. The fourth plot (middle right) shows that the 24-satellite constellation is less sensitive than the 21-satellite constellation to a single satellite failure. The fifth plot (bottom left) shows that the 24-satellite constellation is sensitive to a single satellite failure. The sixth plot (bottom right) shows that the 27-satellite constellation is less sensitive than the 24-satellite constellation to a dual satellite failure.
design and management decisions were based on the need to achieve optimal performance within reasonable operational loads and cost constraints.

Requirements and Demands

Recently, the aging of the constellation did not permit a minimum 15–20 minute outage that repeated daily over portions of Texas and Oklahoma. While this outage was small compared to what one would expect under steady-state conditions (when failures and launches occur at roughly the same rate), the region that was affected did not consider it small at all. Concern over the outage and its impact on civil transporta-
tion systems prompted officials to reposi-
tion one of the older satellites and retarget a launch to a compensated service over the affected area.

This incident clearly demonstrates the dichotomy that has developed between user expectations and design objectives. GPS was not designed to provide continuous, uninter-
rupted global coverage. While global coverage has always been an objective, it has been pursued only within the limits of budgetary constraints.

For example, the size of the constellation was adopted to balance user demands for maximum coverage against govern-
ment demands to constrain cost. If global coverage were the only goal, then a larger constellation would be needed. However, to achieve the best coverage and robustness at all times within the stipulated budgetary constraints was not possible. In the past, user expectations of the constellation size were not sufficient to ensure that the constellation size never fell below 24.

Aged satellites were not launched until the primary satellites had aged enough to provide as much coverage as possible in the event of a single satellite failure. But although the optimization reduced the outages experienced with failures, it did not eliminate them all. The Air Force considered available computer power to improve modeling accuracy, so the constellation was optimized again to emphasize as-
sured service over robustness. With the redesigned constellation, the degradation in accuracy experienced during satellite failures was less severe. Moreover, outages after a satellite failure would not be significantly worse than with previous generations, although the overall trend for outages between satellites was not.

All constellation design and management decisions were based on the need to achieve optimal performance within reasonable operational loads and cost constraints.

Launch and Management

The GPS program office targeted initial Block B launches to occur in the late 1980s from Yuma (to facilitate testing). After the first of the first launches, remaining launches were targeted to improve global coverage as quickly as possible, with the exception that after Iraq invaded Kuwait, one launch was altered to provide better coverage over the Persian Gulf.

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satellite constellation, the Defense Depart-
ment determined that GPS had the resources to support a 24-satellite constellation. This decision was based upon the strong perfor-
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sition were conducted after full deployment, the program office began the transition to the 24-satellite constellation midway through the launch schedule. This action fulfilled the Air Force requirement that initial full constellation be achieved as soon as funding permitted. The Pentagon reviewed the decision and consequently decided to support not only the 24-satellite constellation but also enough spares to ensure that the constellation size never fell below 24.

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EELV: The Next Stage of Space Launch

Randy Kendall

The end of the Cold War forced a retrenchment of many defense programs in the 1990s. Congress asked the Department of Defense to generate a plan for ensuring access to space despite increasing budgetary constraints. The resulting Space Launch Modernization Plan of 1994, developed with the participation of The Aerospace Corporation, presented various alternatives ranging from no change at all to a complete overhaul of the space-launch acquisition strategy. The Evolved Expendable Launch Vehicle (EELV) concept was ultimately chosen, as it offered the best approach for managing cost and risk.

The EELV program was designed to reduce the cost of government space launches through greater vehicle modularity, component standardization, and contractor competition. Aerospace helped develop system requirements that emphasized simplicity, commonality, standardization, new applications of existing technology, streamlined manufacturing capabilities, and more efficient launch-site processing. In fact, the EELV System Performance Requirements Document listed only three “key performance parameters.” These stipulated specific mass-to-orbit requirements for each class of vehicle, design reliability of 98 percent at 50 percent confidence level, and standardization of the launchpads and payload interface.

The first Atlas V lifted off from Cape Canaveral on August 21, 2002. This launch marked the first operational use of a rocket designed under the EELV’s joint Air Force/industry partnership.

U.S. launch capabilities continue to evolve to meet increasingly demanding space asset requirements. Aerospace is helping to ensure that the latest generation of advanced launch vehicles will lead a long and productive life.

(The article has been updated since its first appearance in Crosslink, Winter 2003/2004.)

The program includes two families of launch vehicles—the Atlas V and the Delta IV—along with their associated infrastructure and support systems. Each is based on a two-stage medium-lift vehicle, augmented by solid rockets as needed to increase payload capability, and a three-core heavy-lift variant. Both have achieved notable successes in their first launches, but the EELV program is still in its infancy, and will need continued scrutiny to ensure that the anticipated gains in cost and reliability will be realized over the long term. In fact, Aerospace involvement in the program was initially limited, as the government sought to position itself more like a commercial customer; however, as the date approached for the first national security launch (for the Defense Satellite Communications System in March 2003), an increased emphasis on mission assurance prompted a return of Aerospace’s traditional role in independent launch verification.

Atlas V Evolution

The Atlas V traces its roots to the Atlas ICBM developed in the late 1950s, although its modern evolution begins with the Atlas IIA, introduced in 1992. The Atlas IIA featured a 5-meter-diameter pressure-stabilized booster tank powered by three liquid-oxygen/kerosene boosters and the first stage used for payloads in low Earth orbit. The Atlas IVA, entered service in 1996, added a 3-meter-diameter booster and a second 5-meter-diameter core. Two versions of the Atlas IVA were developed: the 551 for national security launches, and the 552 for civil launches.

As the government’s needs evolved, it became apparent that the Atlas IVA was no longer a competitive option in the commercial and national security market. The new Atlas V was designed specifically to meet the needs of the evolving commercial industry and national security market. In October 2002, a hot-fire ground test at the Redstone Arsenal set the stage for the first flight of the Delta IV in November 2002. The Delta IV uses the first liquid-fueled rocket engine (the RS-68) designed, built, and flown in the United States in more than 20 years.

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sustainer engines producing 2.1 meganew- 
tons of thrust at sea level. The rocket’s upper 
stage—the Centaur II—was also 3 meters in 
diameter and featured a dual RL10A-4 en-
gine. The avionics that control the Atlas were 
located on the Centaur, with booster-specific 
components residing in avionics pods at-
tached to the outside of the first stage. In 
this configuration, the Atlas IIA could lift 3066 
kilograms to a geosynchronous transfer orbit.

The Atlas IIA, introduced in 1993, used four solid rocket boosters to increase performance to 3720 kilo-
grams to geosynchronous transfer orbit. The next major Atlas variant, the IIA, success-
fully flew on its first attempt in May 2000. This vehicle included the Russian-built RD-180 engine, which is also featured on Atlas V. Use of the RD-180 pre-
sented significant challenges for the government and Aerospace in con-
ducting flight verification activities because access to the engine’s design and test data was restricted. (A U.S. coproduction capabil-
ity is now being developed as a risk-reduction effort.) Fueled by liquid oxygen and kerosene, the RD-180 has two chambers fed by a common turbopump using a staging combustion cycle to deliver 3.8 meganewtons of thrust. To accommodate a higher mixture ratio, the liquid-oxygen tank was lengthened approxi-
ately 4 meters. The Atlas IIA was also the first to use the Centaur III upper stage. In this 
configuration, the Atlas IIIA can lift 4060 kilograms to geosynchronous transfer orbit. The Atlas evolution continued with the IIB, first flown in February 2002. This ve-
hicle introduced the Common Centaur upper 
stage, which can be flown with either single or dual RL10A-4-2 engines. The Atlas IIB 
can lift 4500 kilograms to geosynchronous transfer orbit. The Centaur tanks on the Atlas IIB were lengthened by approximately 1.7 
meters more than the IIA; as a result, Aero-
space recommended additional structural qualification testing, which was completed in 
the spring of 2004. The Atlas IIB was designed to be used in the introduction of the 3.8-metric-ton Common Core Booster, which forms the 
basic building block of all Atlas V vehicles. Upgrades to avionics and redundant systems were also incorporated. The Atlas V 
core vehicles can be equipped with payload fairings measuring 4 or 5 meters in diameter; the 4-meter version can carry up to three solid 
rockets, and the 5-meter version can carry up to five. A heavy-lift version, still in develop-
ment, will consist of three Common Core Boosters strapped together. All variants use the same main engine, core booster, Com-
mon Centaur, and avionics. This common-
ality enables the Atlas V to support a wide 
range of missions and facilitates upgrades from one variant to the next if performance requirements increase. In fact, the Atlas V is the first Atlas that can support direct injec-
tion into geosynchronous orbit. The 4-meter 
vehicles can lift 4950–7620 kilograms to geosynchronous transfer orbit, the 5-meter 
service can lift 3950–8665 kilograms, and the 
heavy-lift vehicle will lift 12,650 kilograms. Launch processing for the Atlas V begins on the “clean pad” concept at Cape Canav-
eral. The benefits of this approach include the ability to launch several Atlas V configu-
ration from the same pad. The vehicle is fully integrated off-pad in a vertical position, 
accommodate the largest 5-meter vehicles, but not the heavy-lift version. Aerospace 
personnel who were involved with previous launch pad upgrades at Vandenberg are help-
ing to support this activity.

The Atlas V prepares for its inaugural launch.

A still frame from the onboard video camera carried by the Atlas V during its inaugural launch. A jettisoned booster section can be seen falling away from the rocket toward Earth.

Photo courtesy of International Launch Services
A New Approach to Launch Acquisition

The Evolved Expendable Launch Vehicle (EELV) program sought to reduce the cost of military space missions by purchasing commercial launch services rather than launch-vehicle hardware, infrastructure, and operations support. The idea was to eventually eliminate the wide variety of expendable launch vehicles—Titan IV, Delta II, Atlas II, etc.—and have all defense payloads fly on one family of EELV rockets. That meant that the launchpad and payload interfaces would all need to be standardized, and the rockets would have to employ a modular design to accommodate different payloads. Standardization would also allow the contractor to use the same systems for commercial launches, and thereby achieve economies of scale that are not typical of military launch programs.

The Department of Defense awarded $30 million contracts to four companies in August 1995 and then $50 million follow-on contracts to two companies in December 1996 with the goal of ultimately selecting just one. This strategy was based on the assumption that the commercial market could not support two launch systems; however, by 1997, the situation had apparently changed.

The worldwide demand for commercial launches into geosynchronous transfer orbit was expected to reach 30–40 per year.

Given this robust commercial market, the government decided to revise its acquisition strategy and allow two contractors to proceed to the engineering, manufacturing, and development phase and receive Initial Launch Service contracts. The Defense Department competitively awarded a $500 million agreement in October 1998 to develop the Delta IV system and signed a $1.36 billion contract for 19 launches. The Atlas-V system also received $500 million for development and a $650 million contract for nine launches.

This cost-sharing arrangement provided only partial funding for the development of the two launch systems. The balance would come from the contractors themselves. In exchange, the contractors would retain ownership and control of all system designs and launch operations and could thus shape their development plans to support long-term strategic goals.

Along with this new acquisition strategy, the military had to rethink its traditional business approach and position itself more like a commercial customer. Consequently, EELV program managers adopted a new stance with regard to mission assurance, risk management, and overall program control. They replaced traditional government oversight with so-called insight, a project management style that allows inline involvement but no actual direction.

No sooner had the Air Force changed its acquisition strategy than the environment changed again. First, the DeltaIII and Titan IV systems experienced significant problems in 1998 and 1999. As a result, the government formed a team, which included Aerospace, to investigate and evaluate potential system causes of failures across all launch systems. During the same period, the projected boom in the commercial market began to fizzle, drastically reducing the number of commercial missions that would occur before the first government missions, thereby diluting the risk reduction benefits that the government had anticipated.

As a result, additional mission-assurance steps were taken. For example, the Department of Defense allocated funds for a demonstration flight of the heavy-lift version of the Delta IV, scheduled for summer 2004. Such a demonstration was not originally necessary because the Delta IV was supposed to establish a track record with commercial launches before carrying any defense payload. However, the government had anticipated failures in 1998 and performed independent validation of the modifications to the flight control software that was determined to be the root cause. Aerospace was also actively engaged in the anomaly resolution following the second Delta III failure that involved the RL10B-2 engine. Prior to the successful third flight, Aerospace personnel provided hardware review and software validation expertise.

The Delta IV Evolution

The Delta IV lineage also traces back to the late 1950s and has its origin in the Thor ballistic missile. The modern evolution stems from the Delta II, which completed its first mission—a GPS satellite launch—in 1989. Subsequent configurations have included the RS-27A liquid-oxygen/kerosene main engine on a core vehicle measuring 2.4 meters in diameter. The RS-27A provides only 0.9 megawatts of thrust at sea level, so with a minimum gross lift-off mass greater than 100,000 kilograms (without solids), the Delta II requires strap-on solid rocket motors for lift-off. The second stage is powered by an engine running on N₂O₅ and Aerzine 50. For high-energy missions, such as a GPS transfer orbit or Earth escape trajectory, a third stage can be added with a solid rocket motor.

The next major development was the introduction of the Delta III with a 4-meter-diameter upper stage powered by an RL10B-2 engine. Fueled by liquid oxygen and liquid hydrogen, the RL10B-2 is similar to the RL10A-4 flown on the Centaur and includes an extendable nozzle. The Delta III uses a shorter and wider fuel tank than the Delta II to accommodate the larger upper stage and payload fairing; this design keeps the overall length roughly the same and allows the Delta III to maintain control authority and to maintain compatibility with existing facilities. In addition, slightly larger graphite-epoxy solid rocket motors are employed.

The heart of all Delta avionics is the redundant inertial flight control assembly introduced in 1995, this assembly uses six ring-laser gyroes and six accelerometers to provide complete redundancy in each axis. Capable of lifting 3810 kilograms to geosynchronous transfer orbit, the Delta III doubled the performance of the Delta II, allowing it to fly a much larger class of payloads. While its success record was not stellar, the Delta III was a critical step forward, enabling Delta to compete in the intermediate and heavy launch market. Although Delta III was an entirely commercial development, Aerospace participated in the anomaly resolution that followed the first Delta III failure in 1998 and performed independent validation of the modifications to the flight control software that was determined to be the root cause. Aerospace was also actively engaged in the anomaly resolution following the second Delta III failure that involved the RL10B-2 engine. Prior to the successful third flight, Aerospace personnel provided software validation expertise.

The Delta IV Family

The final step in the evolution of the Delta IV brought the Delta III 4-meter-diameter upper stage to a new 5-meter-diameter Common Booster Core. The core’s RS-68 main engine is the first liquid-oxygen/liquid-hydrogen main engine developed and flown in the United States since the space shuttle. It uses a gas generator cycle with a relatively low chamber pressure. Although it has significantly lower specific impulse than the space shuttle main engine, it produces almost twice the thrust and is much simpler and cheaper to produce. Aerospace provided significant support during the development and testing of this engine, including the resolution of several thermomechanical vibration issues.

The Delta IV Common Booster Core appears on all vehicles in the Delta IV family, with some tailoring of skin thickness to optimize weight as appropriate. The complete Delta IV family includes three classes of vehicles—medium, medium-plus, and heavy. The medium vehicle comprises a Common Booster Core and a 4-meter-diameter upper stage and payload fairing. The medium-plus vehicle includes a version with a 4-meter-diameter payload fairing and two solid motors and a version with a 5-meter-diameter upper stage and one or two, or four solid motors. The heavy-lift vehicle, similar to Atlas V, comprises three cores strapped together. The Delta IV medium can lift 4210 kilograms to geosynchronous transfer orbit, while the medium-plus variants can lift 4640-6565 kilograms and the heavy-lift vehicle can carry up to 15,130 kilograms.

The first Delta IV system launches from two pads on the East and West coasts. The launchpads themselves are fairly conventional, with mobile service towers to provide protection from the environment and access to the vehicle and payload. The launch vehicle is processed off-pad in a horizontal position. The first stage is mated to the upper stage in the processing facility, and the vehicle is then rolled out to the pad and hydraulically rotated to vertical on the launch table. The encapsulated payload can then be hoisted and mated to the launch vehicle, followed by the second and third stages. On the day of launch, the mobile service tower is rolled back prior to propellant loading approximately 8 hours before launch.

Standard Payload Interfaces

Along with the improvements in performance, reliability, and operability, one of the most significant achievements of the EELV program was the development of a standard interface for all EELV payloads. The Standard Interface Specification was
developed by a joint government-industry team with representatives from launch vehicle and space vehicle programs; Aerospace served as the technical coordinator. The document includes more than 100 requirements for all aspects of the launch vehicle/space vehicle programs; Aerospace provided the same standard interface is a significant improvement over the heritage systems, where moving from a Delta II to an Atlas II or from an Atlas II to a Titan IV was highly complex, if at all possible.

The Next Steps
The Delta IV and Atlas V have successfully completed four and five launches respectively. Atlas V has flown five commercial communications satellites on the 4- and 5-meter configurations. Delta IV has launched two Defense Satellite Communications System spacecraft on medium vehicles, a commercial communications satellite on a medium-plus vehicle, and a heavy-lift demonstration flight funded by the Air Force. On the day of launch, Aerospace personnel supported the government mission director by monitoring prelaunch and flight data from specialized facilities at the launch site and in El Segundo.

The heavy-lift launch demonstrated the capability of the ground and flight systems for the heavy-lift vehicle configuration and successfully met a number of primary objectives; however, the mission did not achieve the desired final orbit, resulting in a missed target altitude for the deorbit (a nonfunctioning payload simulator) and two secondary payloads. The anomaly involved a prematurely commanded shutdown of all three of the RS-68 engines. The anomaly investigation determined root cause to be related to the presence of gaseous oxygen in the liquid-oxygen feedline, resulting in an erroneous ‘dry’ indication on the depletion sensor, thus triggering the premature shutdown. The comprehensive postflight analyses conducted by both Aerospace and the contractor indicate that all other aspects of the system performed well, and if not for the premature shutdown, the payload would have been injected right on target. Aerospace had performed numerous independent reviews and analyses as part of its launch verification process, and had highlighted to the air force a number of technical risks and mitigation plans for the first-of-a-kind vehicle. The preliminary data reviews seem to indicate that all risk areas identified prelaunch were successfully mitigated. The mission also underscored the wisdom of the Broad Area Review panel, which recommended in 1999 that a heavy-lift demonstration mission be funded prior to the first operational flight as a risk-reduction measure. Although the commercial market remains weak, the EELV contractors have already been awarded 26 more government launch contracts, with up to 20 more expected to be awarded in fall 2005. While the expected cost efficiencies (based upon large numbers of commercial launches) have not yet materialized, the program is still meeting its cost-reduction goals—even with expected price increases in the next procurement round. The primary reason is that many of the payloads that can fly on an EELV intermediate variant would have required a much more expensive Titan IV vehicle in the past. The government is currently developing the acquisition strategy to be used for this next round of launch service buys, with the challenge of ensuring that both contractors will be able to remain viable competitors in this reduced market. Aerospace is working hand-in-hand with the government to ensure that the new contracts properly incentivize the contractors for mission success as well as assured access to space.

Acknowledgement
The author thanks Pete Portanova for his contributions to this article. •
Maximizing the Value of Intellectual Property

Andrew Quinntero

Aerospace has a formal process to explore and develop ancillary applications for technology originally developed to support the national security space community.

Many of the innovations developed at Aerospace are the direct result of specific problem-solving efforts for the company’s government customers, while others are the unexpected byproducts of independent research activities. Truly novel discoveries generally result in patents, which help fund research requests that might not. In turn, Aerospace makes direct and serves to protect the government's investment and serve to protect the government's investment and enhance its overall value to the government and the commercial sectors. Using an active approach and leveraging the talents and resources from outside entities, Aerospace has developed a unique, inexpensive, and attractive valuing solution that will significantly advance the lab-on-a-chip industry. Discussions are taking place to explore the possibility of forming a new company to offer this technology on a broad scale.

Summary

Aerospace has established a formal approach to expanding the utility of its intellectual property by maximizing its overall value to the government and the commercial sectors. Using an active approach and leveraging the talents and resources from outside entities, Aerospace has developed a unique, inexpensive, and attractive valuing solution that will significantly advance the lab-on-a-chip industry. Discussions are taking place to explore the possibility of forming a new company to offer this technology on a broad scale.

Patents Awarded in the Past Five Years to Aerospace

<table>
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<tr>
<th>Inventors</th>
<th>Title</th>
<th>Patent Number</th>
<th>Date</th>
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<tr>
<td>G. L. Liu and K. Tsao</td>
<td>&quot;Data Aided Symbol Timing System for Precise Continuous Phase Modulated Signals&quot;</td>
<td>U.S. Patent No. 6,632,324</td>
<td>Mar. 2004</td>
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The Licensing Process

The licensing process begins by capturing what is in the mind of the inventor. When an Aerospace researcher discovers a truly novel concept, the information is recorded, and the invention is listed in the intellectual property database. The invention is then presented to one of four patent review committees, depending on the subject matter. If the committee approves going forward with a patent application, an outside patent attorney, under the direction of the General Counsel’s staff, will begin preparing it, and the Office of Intellectual Property Management will assist the inventor in preparing a one-page summary and 12-page briefing. The invention disclosure and patent must be filed before strong public disclosure of the invention, as a professional paper or conference presentation, is made. Certain rights to the patent both domestically and abroad can be lost if a public disclosure is made prior to filing the patent with the United States Patent and Trademark Office.

After the patent application is filed, licensing opportunities can be explored. The government can take several years to actually issue a patent, but many technologies have cut through the process in less than a year. The government need not be involved for the technology to be licensed.

To identify prospective licensees, Aerospace presents “Technology Opportunity” briefings at industry events and to venture capital advisory boards, primarily in the San Francisco Bay area (because of its proximity to the high-tech activities of Silicon Valley). Most of these events are sponsored by a nonprofit spin-off of NASA Ames Research Center known as the Girvan Institute of Technology: A Los Angeles office of Girvan is expected to open soon.

Once a formal request to license the technology is received, a term sheet is drafted outlining the primary intent and conditions for the license to begin negotiations. When all terms are agreed upon, they are embodied in a formal licensing agreement. This agreement delineates the rights, restrictions, and conditions dictated by Aerospace’s role in managing a federally funded research and development center that must protect the government’s interest in this technology. The agreement also details the financial terms, which generally include a license execution fee, recurring minimum royalties, and a performance driver in the form of a minimum fee due in certain years. Revenues are split three ways and distributed to the inventors, their departments, and the corporation’s general funds.

Success Stories

Aerospace’s licensing activities have significantly increased over the last three years. The licensees come in many forms—individual entrepreneurs, small startups, large firms—and each presents varying needs for single patents, bundled patents, and sometimes patent assignees. All agreements are tailored to provide reasonably easy access to the intellectual property in the hope that it will serve a useful purpose. Aerospace frequently provides some advice and assistance to help its licensees under the terms of the license agreement. More extensive assistance, if any, would be rendered through an agreement for a fixed fee, royalty, or license fee.

For example, representatives of a large Australian defense contractor working on various homeland security projects with the U.S. Department of Homeland Security homeland security agencies met with Aerospace at Girvan. They discussed whether some Aerospace technology could be used to collect and send information from within a cargo container as a way to monitor such containers containing major ports—a serious security concern. After considering the problem, Aerospace offered a solution using a patented technology employing acoustic waves to transmit power and data through a structure. Aerospace originally developed the technique as a means of monitoring launch vehicles during transport from a manufacturing facility to a launch complex. Aerospace realized that although this technique was originally designed to detect unexpected shocks that would warrant investigation, it could be used to create an acoustic modum that would penetrate a shipping container wall, passing the data to a device on the exterior that could then complete the link to the rest of the communication network. This patent has since licensed the rights to use the Aerospace patent for this application and has contracted with a company to develop and test prototypes for further development.

Sometimes, Aerospace patents provide the basis for a new startup company. One such venture, formed in 2003, is OPL Systems (for Orientation, Pouting, and Leveling), which licensed a patent on a miniature GPS-based altitude determination technology developed at Aerospace. The technology arose through efforts to augment the inertial measurement units used for rocket navigation with a GPS-based unit. OPL Systems was created solely to generate products based on this patent.

Another company, Invenios Technologies, founded in Santa Barbara, found that its current micromanufacturing technology was a great complement to a set of Aerospace techniques using ultra- violet lasers to fabricate and define sensitive surfaces structures. Glass lasers developed these techniques to advance the concept of a miniature glass satellite, but clearly the technology had great potential for many other applications. In the two years since Invenios licensed the technology, the company has established four laser processing stations and has developed a variety of products that will begin shipment this year. Although most of their products will be geared toward creating microfluidic biological devices, one of their first products was a glass ink jet printer head for industrial grade printers.

In a similar vein, the pharmaceutical and biotechnology industries have spent millions of dollars on research and development of mimicry systems, which allow small amounts of liquid samples. Although the channels can be manufactured simply enough, there are no simple ways for including miniature valves. Aerospace may have accidentally discovered the most attractive solution to this problem as a result of a failure investigation several years ago. An examination of a propulsion line revealed that it became plugged when the liquid inside froze. The cause was attributed to the so-called Peltier effect, the cooling effect that can occur when a large current passes through a Peltier element, in essence cooling the liquid to its freezing point. Researchers realized that by intentionally placing a Peltier element close to a small flow channel, the channel could be cooled and warmed to generate a valving and pumping effect. Not much was done beyond filing for patents in the late 1990s, but in 2000, Aerospace became aware of the problem of controlling fluids in such medical diagnostic devices. With a small amount of funding, Aerospace built a prototype to assess whether the Peltier technique offered a viable approach. Feedback from industry experts suggests that Aerospace may have developed a unique, inexpensive, and attractive valving solution that will significantly advance the lab-on-a-chip industry. Discussions are taking place to explore the possibility of forming a new company to offer this technology on a broad scale.
Crosslink Winter 2002/2003

The full text of these articles can be found at http://www.aero.org/publications/crosslink.

**Active Microwave Remote Sensing**

Daniel D. Evans


Active microwave sensing—which includes imaging and moving-target-indicating radar—offers advantages over other remote-sensing techniques.

**Adaptive Nulling Antennas for Military Communications**

Robert B. Dybdal and Don J. Henshield


Aerospace has successfully applied the technology of adaptive nulling antennas to satellites and ground terminals for two Air Force Space and Missile Systems Center programs.

**Aerospace Photos Capture Launch Clouds**

Robert N. Altenhaupt

Vol. 1, No. 2 (Summer 2000)

A new and improved method of measuring launch-vehicle cloud loads leads to fewer launch delays and reduced costs.

**The Air Force Space Shuttle Program: A Brief History**

E. J. (Joe) Tomes


The Air Force has high hopes for its West Coast shuttle complex, but despite years of preparation, this state-of-the-art facility never saw a shuttle launch.

**Antijamming and GPS for Critical Military Applications**

Anthony Abbott


The Delta 183 program was proposed in 1988 for decades, Titan boosters have provided unflagging medium and heavy launch capacity for critical military payloads.

**Atomic Clocks Meet Laser Cooling**

Steven R. Strom

Vol. 5, No. 2 (Summer 2004)

Using bandwidth-efficient modulation, communication satellites can transmit signals through a smaller frequency band, one such technique has yielded benefits for the military’s protected communication satellites.

**The Best Laid Plans: A History of the Manned Orbiting Laboratory**

Steven R. Strum

Vol. 5, No. 2 (Summer 2004)

In the mid to late 1960s, an ambitious project to launch an orbital space laboratory for science and surveillance dominated life at Aerospace.

**Building Space Instruments in the Space Science Applications Laboratory**

Lynn M. Friesen and Dan J. Matby

Vol. 2, No. 2 (Summer 2001)

When commercial alternatives can’t be found, Aerospace steps in to manufacture hardware and instrumentation for research purposes.

**The Challenge of Shared Military Communications**

Mak King and Malina M. Hills


European military satellite communication technologies have never reached the level of their U.S. counterparts—and the gulf appears to be widening.

**Charting a Course Toward Global Navigation**

Steven R. Strum

Vol. 3, No. 2 (Summer 2002)

In the 1960s, the Global Positioning System emerged as a radical new way to provide precise navigation for U.S. armed forces.

**Civilian Uses of Surveillance Satellites**

Dee W. Pack, Carl J. Rice, Barbara J. Tressel, Winfred L. Battig, and Edgar M. Oshika

Vol. 1, No. 1 (January 2000)

Scientists at Aerospace recently designed a laser-cooled atomic clock, specifically intended for cooled atomic clock, specifically intended for the development process.

**Crosslink Five Years of Crosslink**

The advent of GPS has brought a major advancement in precision weapon delivery.

**EELV: The Next Stage of Space Launch**

Diana M. Johnson and Dean J. Sklar


The Delta 183 program was proposed in 1988 for decades, Titan boosters have provided unflagging medium and heavy launch capacity for critical military payloads.

**Evolution of the Inertial Upper Stage**

Glen Elfers


The next generation of geostationary environmental satellites—GOES-R—has the potential to generate a significant scientific advancement in terms of the quality and quantity of meteorological and environmental data.

**Future Launch Systems**

Robert Hickman and Joseph Adams


Fast, cheap, and reliable space launch capability would be a tremendous asset to defense, civilian, and commercial organizations alike.

**Future U.S. Military Satellite Communication Systems**

Glen Effers and Stephen B. Miller


To meet the heightened demands of national security in the coming years, new and more powerful military satellite communication systems are being developed.

**Going the Distance: GOES-R and the Future of U.S. Geostationary Environmental Satellites**

Nathan Feldman, Samuel Lin, Michael Maden, Jim O'Neal, and Kenneth Doss


The next generation of geostationary environmental satellites—GOES-R—represents a significant technological advancement in terms of the quality and quantity of meteorological and environmental data.

**GPS/Inertial Navigation for Precise Weapon Delivery**

Anthony Abbott

Vol. 3, No. 2 (Summer 2002)

The advent of GPS has brought a major advancement in precision weapon delivery.

**Ground Testing of Spacecraft Materials**

Wayne K. Stuckey and Michael J. Meshishnek

Vol. 4, No. 2 (Summer 2003)

Spacecraft paints, films, and coatings are more than cosmetic—they contribute to the vehicle's thermal design.
Launch Vehicle Propulsion
Jeffery L. Einder

Aerospace has helped define a rigorous design and verification process to ensure that launch vehicles and spacecraft withstand the severe forces encountered during launch and ascent.

Medium Launch Vehicles for Satellite Delivery
Joseph P. Weanbord
Vol. 7, No. 2 (Summer 2004)

Aerospace has been instrumental in defining a new GPS system architecture that will ensure military, civilian, and commercial navigation needs are met far into the future.

Positioning System Positioning System
Colleen H. Yingler
Vol. 2, No. 4 (Summer 2002)

GPS was originally designed for defense operations, but civilian receivers now far outnumber military receivers.

Optimizing Performance Through Constellation Management
Paul D. Massam and Wayne Brady
Vol. 3, No. 2 (Summer 2003)

Aerospace has been instrumental in answering the fundamental questions of GPS constellation management: how many, how high, how close, and how long.

Orbit Determination and Satellite Navigation
John Langer, Thomas D. Powell, and John Cox
Vol. 3, No. 2 (Summer 2003)

A satellite system designed by Aerospace is used to diagnose radiation-hardened devices and to validate radiation-hardening techniques for mitigating the effects of space radiation on integrated circuits.

Protecting Space Systems from Lightning
A. Calta, R. Rivers, H. C. Koons, Richard L. Walterscheid, and Richard Britt
Vol. 7, No. 2 (Summer 2005)

Aerospace approaches lightning protection from both spacecraft design and lightning protection perspectives.

Spacecraft Effects of Radiation
Aerospace investigations into SOFIA and HOPE spacecraft interactions with integrated circuits and other electronics have been helping spacecraft designers and mission planners minimize the risk of component failure or performance degradation.

American spacecraft together for the first time—and Aerospace helped arrange the meeting.

Synthetic-aperture imaging
Walter F. Bieb, Nick Marchal, Joseph B. Back, Richard Dickinson, David Kozlowski, Timothy J. Wright, and Steven Becht
Vol. 5, No. 2 (Summer 2004)

Aerospace has been developing a remote-sensing technology that combines ultrahigh-band coherent laser radar with synthetic-aperture signal processing to achieve high-resolution two- and three-dimensional imaging at long range, day or night, with modest aperture diameters.

That’s Why They Call it Rocket Science
Edward Ruth

It is why so hard to launch a rocket into space with double assurance of success?

TSX-5: Another Step Forward for Space-Based Research
Michael L. LaGrasse and James R. Farin
Vol. 7, No. 2 (Summer 2004)

Aerospace provided timely contributions to the overall mission success of the TSX-5 research satellite, including verification of solar-array deployment, validation of critical components, mitigation of potential anomalies, thermal modeling, contamination analysis, and anomaly resolution.

Water-Vapor Lidar Extends to the Tropopause
John Wurtele and W. Farley

Lidar’s role in obtaining accurate measurements of water vapor in the upper troposphere is becoming increasingly important.

What Could Go Wrong? The Effects of Ionizing Radiation on Space Electronics
Allyson D. Yarbrough and John Scarpulla
Vol. 4, No. 2 (Summer 2003)

Aerospace investigations into SOFIA and HOPE spacecraft interactions with integrated circuits and other electronics have been helping spacecraft designers and mission planners minimize the risk of component failure or performance degradation.
This chart shows the lineage of major U.S. space launch vehicles. Many trace their roots to the V-2, brought back from Germany after World War II. Preeminently, the United States had been developing rockets, such as Corporal, but none was as sophisticated as the V-2.

The postwar period saw the birth of the Army’s Aerobee and Bumper (the first two-stage rocket) and the Navy’s Viking sounding rockets. Viking was chosen as the first stage and Aerobee as the second stage for the Navy’s Vanguard rocket. Vanguard later lent components and systems to Thor and its successor, Delta, as well as the small Scout rocket and the Air Force’s Atlas Scout. America’s first solid-fuel launch vehicle capable of putting a satellite into orbit, it took its first stage from the Navy’s Polaris missile and upper stages from Vanguard. Polaris technology would also find its way into Minuteman ICBMs. Minuteman technology is now used to build small launch vehicles such as Pegasus and Minotaur.

Another early weapon program led to the Navaho cruise missile. Although the Navaho program did not last long, its legacy is significant. The Navaho booster engine, adapted from the V-2, was used in the development of Atlas, Redstone, Jupiter, Thor, and Titan I. Atlas D, the first operational ICBM, was deployed in 1959. These missiles were later refurbished as space launch vehicles. Delta, as well as the small Scout rocket and the Air Force’s Atlas Scout, was America’s first solid-fuel launch vehicle capable of putting a satellite into orbit; it took its first stage from the Navy’s Polaris missile and upper stages from Vanguard. Polaris technology would also find its way into Minuteman ICBMs. Minuteman technology is now used to build small launch vehicles such as Pegasus and Minotaur.

Athena I/II, Peacekeeper, Delta IV, and Minotaur are shown at the bottom of the chart. The Back Page Rocket Genealogy (Previously published in Crosslink, Winter 2002/2003)

The first Titan ICBM was deployed in 1962. Development of Titan II began the same year. Many variants of Titan III emerged, including the IIIC and 34D, whose solid motors were derived from Minuteman. The seven-segment Titan ICBM, conceived but never built for the canceled Manned Orbiting Laboratory, later resurfaced as Titan IV.

Atlas III and Delta III are shown at the top of the chart. Centaur was the first American high-energy, liquid-hydrogen/liquid-oxygen rocket. Until 1974, Centaur was used exclusively with Atlas. It was later used with the Titan III and IV boosters and contributed to the Saturn series.

Propulsion system concepts and technologies from Saturn V and Titan III were applied to the space shuttle, whose main engines in turn contributed to the RS-68 engine used on Delta IV.
Jupiter’s Newest Satellite

Gabriel Spera

Peering through his homemade telescope nearly 400 years ago, Galileo first laid eyes on the four largest moons of Jupiter, now known as Io, Europa, Ganymede, and Callisto. His observations caused a notorious stir among his contemporaries, forcing a profound shift in the accepted model of the cosmos. It’s only fitting, then, that Galileo’s namesake spacecraft should cause an equal sensation by indicating that these moons might hold vast saltwater oceans beneath their icy surfaces. Indeed, data from the Galileo craft suggest that liquid water on Europa made contact with the surface in geologically recent times and may still lie relatively close to the surface. If so, Europa could potentially harbor life.

Based on this possibility, NASA is developing ambitious plans for a new mission—the Jupiter Icy Moons Orbiter, or JIMO—that would orbit Callisto, Ganymede, and Europa to investigate their makeup, history, and potential for sustaining life. Sending a spacecraft halfway across the solar system is hard enough, but getting it into and out of three separate lunar orbits will be a tremendous feat, requiring a significant amount of energy. Thus, JIMO will be a new type of spacecraft, driven by nuclear-generated ion propulsion.

The technology will be challenging, but the rewards will be significant: An onboard reactor could support an impressive suite of instruments far superior to anything that could be sent using traditional solar and battery power. It could even be used to beam power to a probe that could be sent using traditional solar and battery power. It could even be used to beam power to a probe or lunar lander.

Aerospace has been lending its technical expertise to the JIMO project. For example, as part of the High-Capability Instrument Concept study, Aerospace helped develop a baseline design for a suite of instruments that can take advantage of the large power supply to achieve high spatial resolution, spectral resolution, duty cycle, and data rates. The candidate instruments included a visible and infrared imaging spectrometer, a thermal mapper, a laser altimeter, a multispectral laser surface-reflection spectrometer, an interferometric synthetic-aperture radar, a polarimetric synthetic-aperture radar, a subsurface radar sounder, and a radio plasma sounder. In addition to generating basic specifications for each instrument, Aerospace explored a number of design options to delineate critical trade-offs. Driving technologies for each instrument type were identified, as well as an estimate of the needed development time. The laser spectrometer, for example, is an entirely new instrument, and the multispectral select-learning approach is based on capabilities that are available in the industry but do not exist in a single design.

Aerospace also performed the maximum revisit times for various inclinations and altitudes and access coverage for the entire moon of Europa. The Re-visit program, a software tool developed by Aerospace, uses simulation and computation. Key results from the study included an analysis of the fields of view needed to achieve the desired mapping coverage. In some cases, the analysis prompted a change in sensor configuration to accommodate sunlight constraints. This analysis also helped define duty cycles that would reduce the amount of data being sent back to Earth without compromising overall performance.

In a related effort, Aerospace engineers analyzed the telecommunications needed for the return of data from the JIMO instruments—and derived a target specification of roughly 33 megabytes per second. Key considerations included loss of communication due to blockage from Jupiter, the sun, and the Jovian moons and the enormous amount of sensor data (even with onboard processing) that will need to be sent. Aerospace provided three system options: direct radio-frequency communication using a 3- or 5-meter dish at 35 gigahertz; laser communication using multiple lasers in the terahertz band; and radio-frequency communication via a relay satellite trailing JIMO.

One particular challenge facing JIMO is the harsh radiation environment. Jupiter has trapped proton and electron belts, much like Earth; however, the Jovian trapped electron environment is much more severe. Planning for this environment will require some new approaches because the most problematic particle around Jupiter is the high-energy electron—not the proton, which is the primary concern around Earth. Aerospace analyses indicate that the radiation challenges are not insurmountable. If commercial integrated circuits continue to evolve at their present rate, they should allow significant improvements in radiation hardness and better protection for both analog and digital flight electronics, including field-programmable gate arrays. Better inherent radiation resistance, along with proper shielding design, should allow JIMO to survive. Still, JIMO will need to overcome the data corruption that will occur as sensitive imagers and spectrometers attempt to collect data in the midst of this severe radiation.

As part of the conceptual mission studies, Aerospace performed independent cost estimates for various configurations and design iterations. The main trades consisted of varying power-conversion types, nuclear-reactor types, and power levels. The cost analysis emphasized technology forecasting, risk, radiation hardening, schedule penalties, calibration of the primary contractor’s historical programs, safety specifications, and responsiveness to other program-management and engineering issues. After each design iteration, the Aerospace and contractor teams met to reconcile their cost estimates. This proved especially valuable because Aerospace was able to influence contractor cost estimates and, in certain cases, the contractor’s cost methodology.

NASA hopes to launch JIMO early in the next decade—and it will probably take another six years to reach its destination. So, it will take some while before scientists crack the secrets of Jupiter’s frozen moons. In the meantime, Aerospace will continue to support the program as needed, joining NASA and other organizations in honoring and advancing Galileo’s great legacy.
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Anniversary Issue Puzzle
Puzzle words and clues are from articles in this issue. The solution is on the Crosslink Web site: http://www.aero.org/publications/crosslink/index.html.

Across
2. They use GPS, too
3. Spacecraft the size of cellphones
5. Bad vibes
11. www.aero.org/careers/jobs
14. Launch vehicle cargo
15. Vehicle family launched from French Guiana
16. New DOD advanced launch vehicles
18. Navigation system or planetary spacecraft
19. Reagan’s “Star Wars” effort
21. It fell into the South Pacific
22. First U.S. astronaut to orbit Earth
24. Intelligence organization, Aerospace customer
25. First AF satellite in orbit under 16 across
26. Reusable launch vehicle
29. World’s most reliable expendable
launch vehicle
34. Funded development for 3 across
35. Federal agency with oversight of 9 down
38. First U.S. space plane
39. Instrument used for Ground Zero analysis
41. Received Gold Medallion from 24 across
44. Second president of Aerospace
45. Last launch in 2005 of this heritage vehicle
47. Enhanced GPS theater support

Down
1. Residence of rocket?
2. Third country to send a human into space
4. Space shuttle lost in 2003
5. “Achilles heel” subsystem of launch vehicles
6. Cirrus Regional Study of Tropical_____
7. Mars mobile scientific instruments
8. Mercury spacecraft name
9. Defense_____Satellite Program
10. Aeronautical achievement trophy won by Aerospace
12. Draper Prize cowinner in 2003
13. Influenced new direction for warfare and intelligence
15. Crewed lunar landing program
17. Aerospace licensed 50 in last 3 years
20. Navy communication system
23. First president of Aerospace
27. Interference in digital communications
28. Calibration method for microwave sensors
29. World’s most reliable expendable
launch vehicle
30. Compton______Observatory
31. Threat to integrated circuits
32. Project______, first U.S. spaceflight with pilot onboard
33. Type of clocks at heart of GPS
36. Manned_____Laboratory
37. Medium for Peter Carián’s analysis sketch
39. Early UK communication satellite
40. Planned surveillance system
42. Number of launch failures in 1998
43. Former USSR