

# Crosslink<sup>®</sup>

The Aerospace Corporation magazine of advances in aerospace technology

Summer 2003

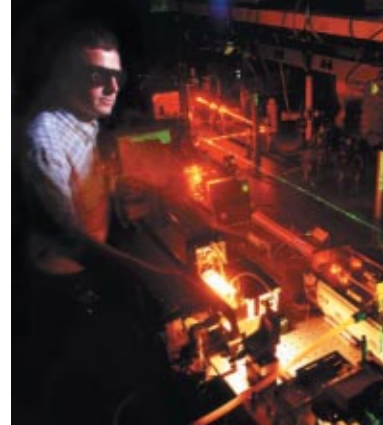
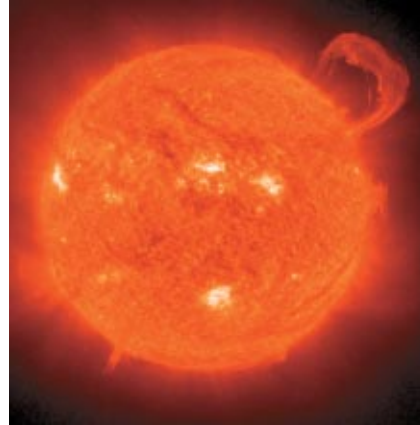


2003 Maggie  
Award Winner

Radiation in the Space Environment

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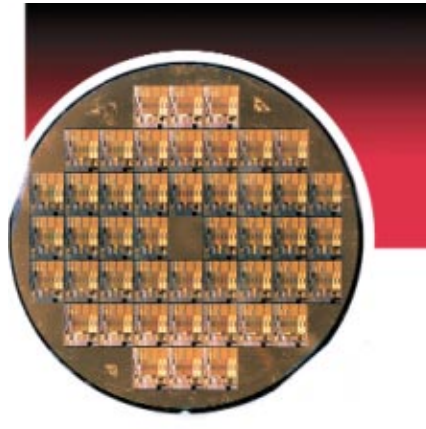
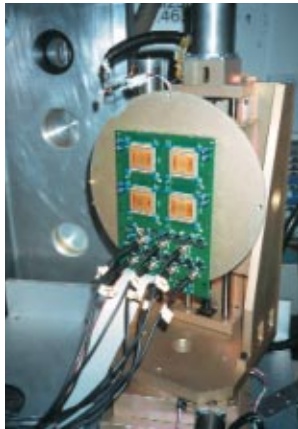
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## From the Editors

Contrary to popular belief, space is not a void. Energetic particles continually speed through the galaxy, bouncing off planetary atmospheres, lingering in magnetic pockets, or passing inexorably through everything in their paths. Like the gremlins of yore, these particles wreak havoc on space electronics, causing flip-flops in memory bits, sending systems into diagnostic mode, and causing circuits to latch up and burn out.

Understanding the behavior of such particles is obviously important to satellite designers. But developing an effective model requires extensive flight data and on-orbit sensing. Aerospace has used its unique resources to conduct the necessary testing, establishing models of particle fluxes that have benefited military, civil, and commercial systems alike.

Modeling the environment is only half the battle. Program managers need to know how well (and how long) their hardware and materials will survive in a given orbit—before launching anything into space. Here again, independent research at Aerospace has yielded tangible benefits. Aerospace helped codify design techniques that achieve some level of radiation resistance without the high cost of traditional processing. Laser simulation of space radiation has helped validate this approach while assessing the suitability of microelectronic parts. Cyclotron testing has helped designers accept or reject critical components, frequently showing that the cost of early testing can pay huge dividends overall.

This issue of *Crosslink* will help readers appreciate the diverse nature of space environment studies and the importance of accurate models and test methods.

## Maggie Award

The Summer 2002 issue of *Crosslink* recently received a Maggie Award from the Western Publications Association as the top semiannual/three-time-published magazine in the Western United States.

## 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



More than 80,000 pieces of debris—roughly 40 percent of the shuttle's mass—were recovered from the Columbia. Here, they are placed within an outline of the shuttle, indicating where they were on the vehicle before breakup.

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 Steckel, 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. "Unparalleled Aerospace scientific and technical capabilities for analyses and modeling and simulation provide the Air Force with a second opinion on virtually every technical issue," he told the board. "The effectiveness of Aerospace's role is significantly enhanced by contractors willing to listen to a second opinion and an Air Force customer that puts mission success above any other objective."

## Nondestructive Inspection

Two of the Space Based Infrared System (SBIRS) satellites are designed to operate in highly elliptical orbits. These units employ optical solar reflectors constructed of thin back-surface reflecting tiles bonded onto heat-rejection radiator panels. After several of these tiles "dimpled" during thermal vacuum testing (see

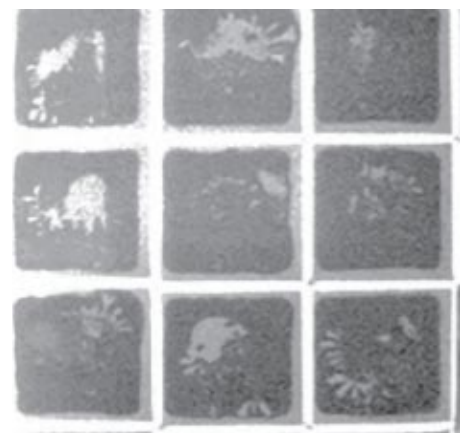


photo, left), Aerospace developed a unique thermographic inspection technique for noncontact inspection of the panels. The technique uses infrared imaging to record the thermal pattern of a test object as it cools down after a rapid but mild heating of the surface. Areas that have an underlying void or debond—which impedes heat transport away from the surface—appear brighter than well-bonded areas because they retain heat longer.

The contractor evaluated several different methods of doing the inspection and concluded that the Aerospace thermograph approach "was the best available," said Harry Yoshikawa of the Space-Based Surveillance division. The contractor requested that Aerospace perform the inspection.

The inspection revealed significant voids in the adhesive below the deformed tiles (see photo, right), resulting in the need to rebond approximately 70 percent of the

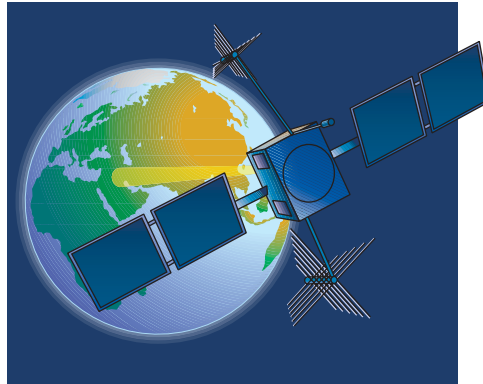
tiles. If the tiles had not been rebonded, the voids would have impeded the heat rejection capability of the panels, causing electronic components to overheat and reducing mission life. The Aerospace technique "is a highly reliable inspection approach and has saved the program much time and money," said Yoshikawa.



## 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 sustain an intensive precision munitions push. Aerospace supported the 2nd Space Operations Squadron (2SOPS) by developing an innovative tactic 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 a 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 advanced notice. "Traditional GETS," said Mendicki, "is very limiting—we can't do it 24/7. Just a few years ago,



round-the-clock enhancement wasn't a major concern, because GPS-guided weapons weren't as prolific as they are today."

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."

## Preventing Pogo on Titan IVB

A Titan IVB rocket successfully launched a Milstar satellite from Cape Canaveral on April 8, 2003. Prior to launch, mission planners were concerned that a so-called Centaur longitudinal event (CLE) could occur during the mission, leading to pogo (undamped dynamic instability), structural failure, and mission loss. Aerospace undertook extensive analysis and test activities to help the contractor identify the source of the problem and adopt corrective action.

Program managers were concerned because an Atlas/Centaur mission in September 2002 experienced dynamic levels much greater than expected and twice as great as a prior identical mission, said Ken Holden, general manager of the Aerospace Launch Verification Division. Moreover, the specific launch vehicle configuration had not been tried before. "The Titan/Centaur for the Milstar mission was the first and only time we had to use Atlas/Centaur RL 10A-4-1A rocket engines to support a Titan

mission," explained Holden. "All other Titan/Centaur missions used RL 10-3-3 engine configurations." Potential impacts for Titan/Centaur were amplified because its propellant system was different from that on Atlas/Centaur, which provided an interactive capability to offset CLE and pogo.

The Air Force, Aerospace, and contractor team conducted additional hot-fire tests on the Atlas/Centaur RL 10 engines. Those tests revealed that under certain conditions, the engine would produce dynamic resonant frequencies through a phenomenon best described as "rotating cavitation." The team then sought ways to limit the risks from rocket engine cavitation and dynamics. "These extremely complex assessments involved the interplay of possible engine dynamics with the Centaur structure and with the Milstar spacecraft's structure," said Holden. "It was ultimately concluded that the initial flight profile for Centaur's mission could result in cavitation in one or both of the RL 10s and that that



might lead to undamped dynamics." Aerospace and the contractor agreed that a mission profile could be designed that would avoid engine cavitation and would not affect mission reliability or accuracy. This was accomplished by increasing inlet pressures to the engines and adjusting the fuel mixture ratios to avoid conditions associated with cavitation, he said.

The Milstar satellite was safely delivered to orbit well within required accuracy. Initial flight data indicate that the Titan booster and Centaur upper stage performed near nominal throughout the mission.

## Keeping the Fun in **FUNDamental Research**

*Cutting-edge research, solid support, and an enthusiastic attitude made life in the Space Physics Laboratory perfect for George A. Paulikas.*

Donna J. Born

When The Aerospace Corporation was forming in 1960, its founders understood that far-reaching scientific research would be needed for military space systems. The laboratories they established soon became world renowned, and the scientists who worked in them were recognized as among the best. One was George A. Paulikas, who came to the company in 1961 as a young scientist fresh out of graduate school and eventually became executive vice president, the corporation's second highest office.

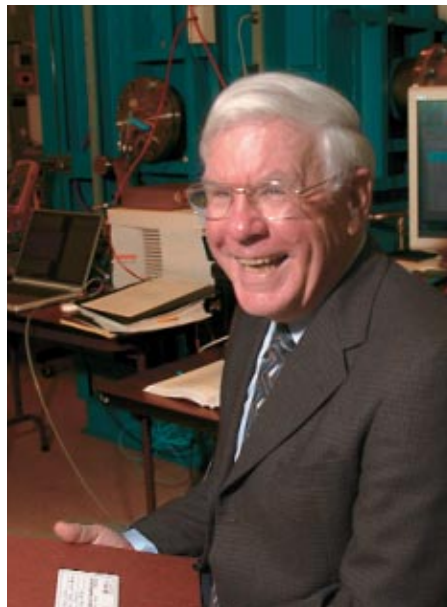
"The space age was just beginning, and I was very interested in space activities, so I decided to go to work in space physics at Aerospace. It was a new company, new organization, and a new field of research," Paulikas recalled. "It was an incredibly exciting time," he added as he recounted with obvious pleasure, even wonder, his long career at Aerospace. And equally important to him, it was fun: "I've been incredibly lucky. Every job I've had, I've really enjoyed."

His initial work in the Space Physics Laboratory was to develop experiments to fly aboard satellites to measure space radiation. Because he and other scientists in the new laboratory were starting programs from scratch, unusual opportunities came their way. One such opportunity came from the Advanced Research Projects Agency, which had contracted General Dynamics in San Diego to build a series of satellites to look at the space environment. But when the program was canceled, ARPA offered the "slightly used" satellites to the laboratory.

"So," Paulikas said, "I went down to San Diego with two Air Force officers, put the satellites on a truck, brought them back here, persuaded the Air Force to pay for integrating them on rockets and successfully flew one of the satellites. It was amazing.

Here I was, you know, 26 or 27 years old, and they handed me and my colleagues millions of dollars worth of spacecraft. It gives you a flavor of how things were in those days."

In the story's sequel, the people who had the original, now obsolete, experiments on those satellites wanted the experiments back. Paulikas laughed and said he felt like



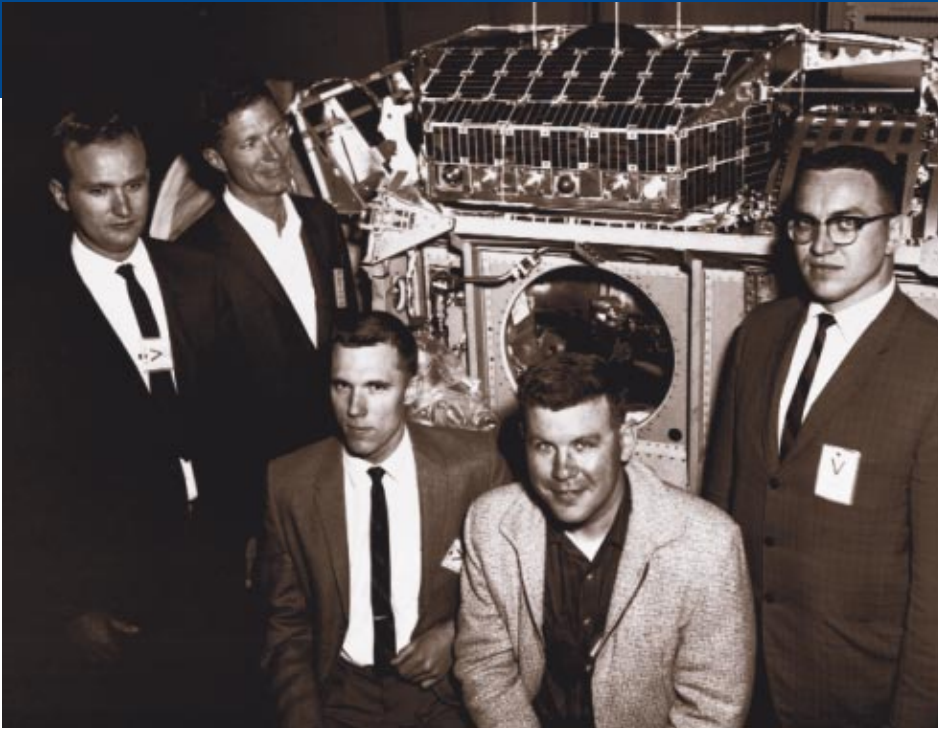
George A. Paulikas helped the Space Physics Laboratory achieve a position of preeminence among scientists studying the effects of space radiation.

General Grant telling General Lee upon his surrender that his men could keep the horses for the spring plowing. He told them, "Sure, you can have the experiments." So the original experiments went back to their owners, but, he continued, "We in the space physics lab, together with scientists from the Air Force Cambridge Research Laboratory, built new experiments appropriate for the orbits in which the spacecraft were going to fly, put these on the satellites, and flew them in the mid-'60s."

Having fun doesn't mean they didn't do an enormous amount of work, Paulikas cautioned. "Let me be clear—we used to work like dogs," he said. "You were always driving up to Vandenberg in the middle of the night, working at the launchpads in the fog and the wind, just freezing. And you're clambering over this rocket... and there were your experiments, and you'd do the checkouts.... It sort of sent shivers down your spine. It was great, and I think that the thing that was fun was we were doing exciting research."

"It was an unusual time," he recalled, "when you could blend truly exciting frontier research with immediately useful applications." He and others in the lab would regularly answer questions about what radiation dose might damage the film flying on a spacecraft, or what would be the effects on the power systems, the solar arrays, or the thermal paints they were flying. In later years, people would ask about spacecraft charging and its effects. During the exciting time when the Apollo astronauts were going to the moon, Paulikas said, the laboratory would get calls asking what the scientists thought the radiation environment was.

People would also ask about the potential effects of cosmic rays. A solar minimum existed in the mid-1960s, but a much more intense emission of energetic particles from the sun occurred in the early 1970s. "In fact," Paulikas said, "in August 1972, there was a huge blast of energetic particles from the sun, and I remember briefing the generals on the effects on the Defense Support Program, for example on the effects of protons from the sun affecting star sensors, which would see false signals because of all the radiation coming in.... Those measurements were some of the earliest of a huge blast of radiation coming from the sun."



George Paulikas (second from right) with other Aerospace scientists (from left) J. B. Blake, J. R. Stevens, J. Mihalov, and A. L. Vampola in front of the first satellite instrumented by the Space Physics Laboratory. The satellite was launched August 1964 on an Atlas Agena to measure Earth's magnetosphere environment.

Funding for the Space Physics Laboratory was never a problem because of “the great support we got both from the company and the Air Force,” Paulikas said. But he frequently remarked on the unusual times when weighty responsibility was vested in young scientists. “I had to go up on the sixth floor [corporate executive offices] and explain what we were doing,” he recalled. “You know, here was this kid explaining what we were going to do with all this money. It was the first generation of Aerospace. And then we persuaded the Air Force into supporting the launches... of our space environment radiation experiments. The one problem with doing anything in space is you need to get your experiments into orbit, so we were forever begging all the program offices to put our experiments aboard [their launches].”

Paulikas was appointed director of the laboratory in 1968 (because, he joked, he was having too much fun as a scientist), a position he held for 13 years. Ivan Getting, the first president of Aerospace, praised Paulikas and his staff, noting in his memoirs, *All in a Lifetime*, that they were internationally recognized for their work in space physics. Paulikas was promoted regularly after that, moving to “bigger and bigger technically challenging sandboxes. As I said earlier, I have been blessed that I have enjoyed every job I’ve had.”

He has received many awards for his work, including the National Reconnaissance Office’s Gold Medal, and in 1981, the company’s highest honor, the Trustees’ Distinguished Achievement Award. The distinction, he explained, “was based on the work that my colleagues and I had done in the 1960s and early 1970s, namely the study of space radiation, the discovery of some new phenomena of the way radiation in space behaves, the input of these data into radiation belt models, and, of course, the work with a large number of program offices to make that data immediately available so that they could proceed and design both spacecraft and sensors aboard the spacecraft that would take into account the effects of space radiation.”

He became executive vice president in 1992. In that position, he said, he derived his greatest satisfaction from ensuring adequate corporate resources to maintain Aerospace’s technical capabilities while he steered the company through both good and difficult years. He retired from Aerospace in 1998, but has since “failed retirement” and continues to work as hard as ever on projects for Aerospace and other organizations. He is on the National Academy of Sciences Space Studies Board, “a committee that overviews all NASA’s space science programs—more

technical challenges, more opportunities to learn.”

His curiosity about the physical world and his image of the world as his sandbox have roots in his childhood, which he described in his book, *Thirteen Years: 1936–1949*. He was born in Lithuania and grew up in Europe, moving continually with his parents, who were preoccupied with the effort to survive during the years of scarcity and hardship during and after World War II. His book, however, describes a happy, almost idyllic Tom Sawyer–like childhood of freedom and adventure as he explored his world unconstrained, wandering through woods, climbing around railroad locomotives, and playing on the river harbor, where he fished, walked on floating logs, and searched abandoned buildings. More questionable adventures involved disassembling live ammunition, the debris of the war, to make fireworks with the gunpowder thus extracted. In the absence of school, his education often came from his engineer father and his teacher mother.

His family eventually immigrated to Chicago, where after high school, he worked at Continental Can company, designing improvements for can-making machinery to pay his way through college. “I still cannot pick up a can of beer without examining the can’s seams,” he laughed. He began his undergraduate work at the University of Illinois Chicago Navy Pier campus, where he first met Bernard Blake, who also came to Aerospace when Paulikas did and still works in the Space Physics Laboratory. He earned B.S. and M.S. degrees in physics at the U. of I. Urbana campus and a Ph.D. in physics at the University of California, Berkeley. It was a professor at Illinois and another at Berkeley who suggested he work at Aerospace.

How would he like to be regarded by his colleagues? “That I enjoy my work,” he quickly answered, but then, with a more serious tone, said, “I would like to think people believe I did the best I could and that I enjoyed all those years. Aerospace was great to me. I had fun, and I was privileged to participate in important projects.” 🌐

# A Decade of Space Observations:

## The Early Years of the Space Physics Laboratory

**George A. Paulikas  
and Steven R. Strom**

*Little was known about the space environment when the space race kicked into high gear, but Aerospace quickly helped fill the knowledge gap.*

The San Fernando Observatory was constructed in 1969 by The Aerospace Corporation at the Van Norman Reservoir near Sylmar, California. It was built for the Space Physics Laboratory with the purpose of conducting solar research.

In its initial mission statement, The Aerospace Corporation pledged “to apply the full resources of modern science and technology to achieving continuing advances in military space systems, which are basic to national security.” Space systems, of course, are subject to the effects of the space environment, yet when Aerospace was established in 1960, many characteristics of that environment were completely unknown. James Van Allen had discovered the first of two major radiation belts surrounding Earth in 1958 after analyzing data from the first U.S. satellite, Explorer I. His work was widely hailed as one of the outstanding scientific achievements of the International Geophysical Year (July 1957–December 1958). And yet, despite

this significant contribution to the study of space environments, many questions regarding the hazards of space radiation for spacecraft and astronauts remained unanswered. Investigating the characteristics of this radiation and applying the knowledge to the operational needs of space systems marked one of the earliest scientific and engineering challenges for the young Aerospace program.

The first president of Aerospace, Ivan Getting, and other early corporate leaders recognized that scientific research was critical for long-term success. From the start, they supported a strong technical research program. Chalmers Sherwin joined the corporation soon after it was formed as vice president and general manager of



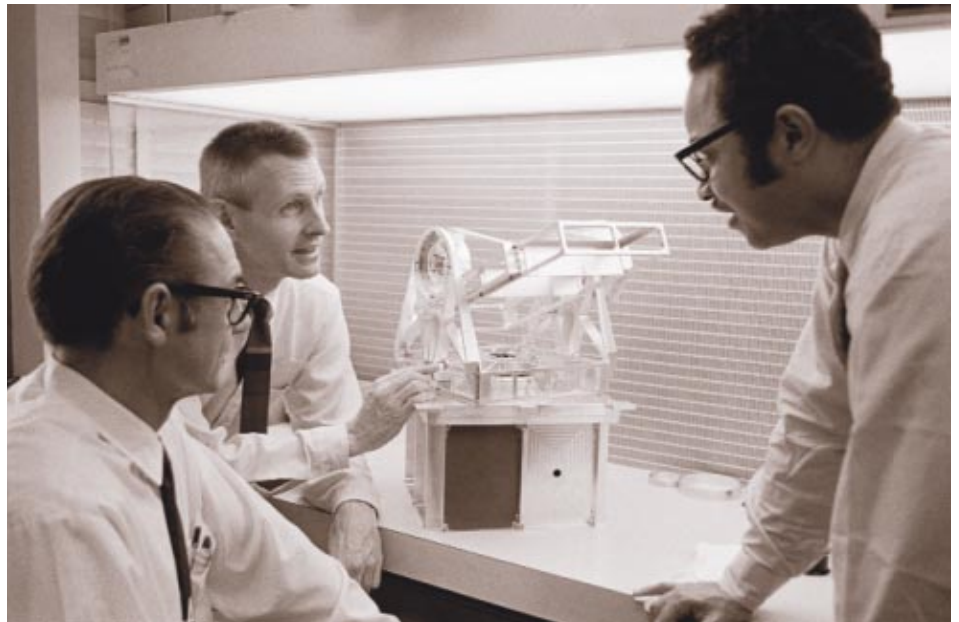


Laboratory Operations, whose goal was “to advance the state of the art in areas critical to achieving continuing scientific advances in the field of ballistic missiles and military space systems.” Early space-radiation studies took place in the Space Physics Laboratory, one of five laboratories in the division. Initially directed by Robert A. Becker, the laboratory made enormous progress toward understanding the dynamics of space radiation and other aspects of the space environment.

Sherwin summarized the tasks and goals of the Space Physics Laboratory in a report for the board of trustees in August 1961. The laboratory’s research responsibilities, he wrote, were to investigate “infrared sources associated with spacecraft” as well as environmental requirements for space weapons systems and military reconnaissance satellites. The laboratory would also formulate “a theoretical basis for the comprehension of the various phenomena which occur in space.”

The report described the laboratory’s considerable activity and notable achievements: Just one year after the founding of Aerospace, the laboratory was supporting the BAMB I Orbital Interceptor System; the VELA Hotel program (a system for detecting nuclear explosions); ADVENT, a geosynchronous communications satellite for the Army (later canceled before completion); and the MIDAS infrared satellite warning system. Laboratory scientists had also made rapid progress in understanding the space environment both inside and outside Earth’s atmosphere. The group had conducted a feasibility study for analyzing the chemical composition of lunar and planetary surfaces and developed flight prototypes for a nuclear detector designed to measure particles in the Van Allen radiation belts, auroral zones, and solar flares. The laboratory had also planned and designed experiments for a vacuum-ultraviolet research program, an infrared-radiation research program, and a program to develop devices to detect nuclear explosions in space.

The rapid pace of experimentation and research during this early period created a stimulating, though challenging, work environment. Laboratory facilities were dispersed throughout the Los Angeles Air Force Base in various offices and trailers stationed in the parking lot. Despite this lack of elbow room, laboratory personnel were excited to participate in Aerospace’s



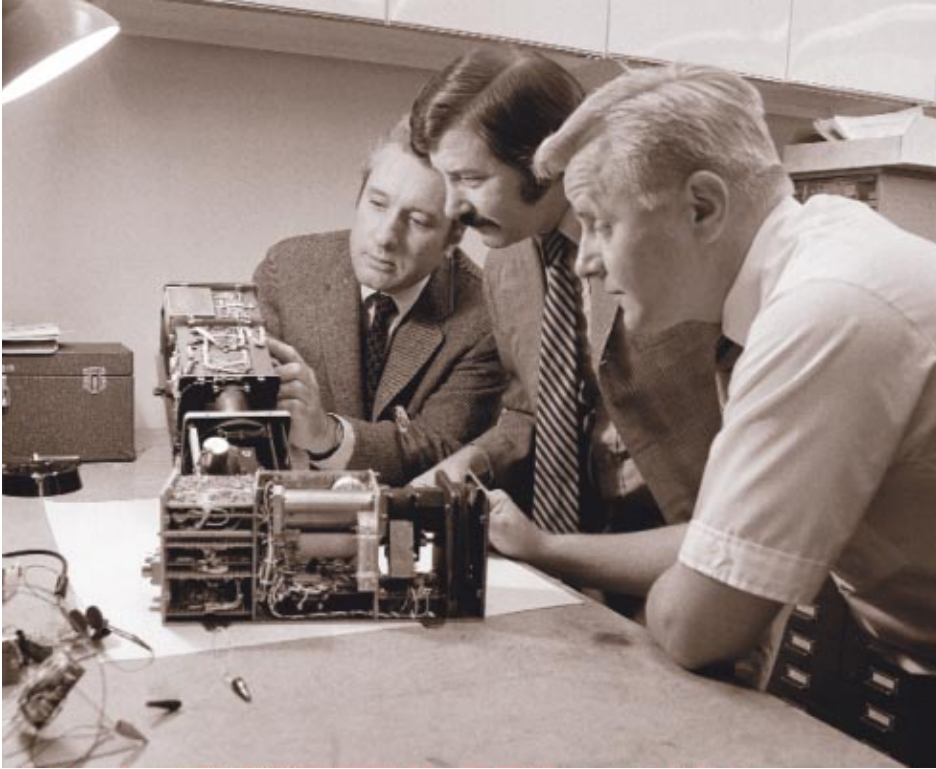
Planning the development of a solar pointer are C. K. Howey, W. T. Chater, and A. B. C. Walker Jr., of the Space Physics Laboratory, circa 1970.

groundbreaking studies. By the summer of 1961, approximately 30 people had joined the lab from various organizations. Steve White and Stan Freden, early pioneers in space physics, came from Livermore National Laboratory; Forrest Mozer and David Elliott from the Lockheed Palo Alto laboratories; John Stevens from Caltech; Bernie Blake from the University of Illinois; and Al Vampola from General Dynamics. Others included Earle Mayfield, Gilbert Cook, Henry Hilton, John Mihalov, Dale Vrabc, and Sam Imamoto. Significantly, an early analysis by Freden and Mozer showed that adequate knowledge of radiation belts did not exist, and the measurement programs proposed by NASA and the Air Force would not provide it—at least not within the next few years, when the Air Force needed it most. Their analysis further spurred the laboratory’s space radiation studies.

Because of its work with the Air Force, Aerospace was particularly well positioned to measure radiation in space and characteristics of the upper atmosphere. Researchers anticipated that their experiments, which required access to space, could hitch rides aboard Air Force launch vehicles. One early series of experiments, for example, flew research payloads into low polar orbit aboard the Discoverer spacecraft (now known as the declassified CORONA reconnaissance program). Plans were also made to place radiation measurement devices aboard ADVENT. In parallel,

Aerospace proposed sending a self-contained, small radiation-measuring satellite on a low-cost booster, such as a Scout. Thus, by early 1962, the Space Physics Laboratory was already exploring the full range of options for studying the space environment.

As with many other programs in the early years of the corporation, space radiation studies received a boost by a startling development in the arms race between the United States and the Soviet Union. Beginning in 1958, the United States had exploded a series of low-yield nuclear devices at high altitudes, but the scale and scope of nuclear testing in space escalated dramatically in the summer of 1962, leading to unforeseen consequences. The United States detonated a high-yield (1.4 megaton) nuclear device, code-named “Starfish,” on July 9 above Johnston Island west of Hawaii at an altitude of 400 kilometers. The enormous explosion created a new radiation belt and produced an aurora that lasted about seven minutes. In the aftermath, the intensity of radiation in space increased a thousandfold. Several spacecraft were damaged or destroyed. The need to understand the characteristics of space radiation now acquired greater urgency, as it was clear that a nuclear detonation in space could conceivably disable military satellites. The sense of urgency was heightened when the Soviets began their own series of high-altitude nuclear detonations later that year.



D. D. Elliott, S. R. LaValle, and R. L. Williams examine photometers to measure altitude and latitude distribution of atmospheric airglow layers, circa 1970.

Research at the laboratory accelerated to a pace that is hardly imaginable today. For example, three radiation-measuring devices flew as secondary payloads on the Agena spacecraft that carried the CORONA payloads into orbit in the fall of 1962. The radiation measurement program evolved and expanded to include plans for not only additional piggyback payloads, but also several types of free-flying satellites flown aboard Scout, Atlas, and Titan boosters as well as additional payloads flown aboard several NASA spacecraft. The measurements obtained through these devices established in greater detail the characteristics of the near-Earth radiation belts—the fluxes, spectra, and spatial distribution of electrons, protons, and alpha particles trapped in Earth’s magnetic field.

Aerospace scientists were able to determine the decay time of the energetic electrons injected into Earth’s magnetic field by the American and Soviet nuclear detonations. The data on space radiation were communicated in real time to Aerospace program satellite offices and, as appropriate, more broadly to the nation’s technical community. With NASA support, Aerospace initiated a program under the leadership of Jim Vette to construct models of the space environment, resulting in the NASA series of AE (Aerospace electron) and AP (Aerospace proton) models of the space radiation environment. These early models and their successors have been instrumental

in establishing standards for space-system design and space radiation protection.

Data obtained from these efforts put Aerospace at the forefront of space radiation studies. By 1962, new findings led to new initiatives, including a program to study the phenomenon of spacecraft charging and its effects on electronic systems. New insights were gained into how Earth’s magnetic field shields the local region of space from solar cosmic rays and how the flow of solar wind modulates radiation trapped in Earth’s magnetic field.

The United States was committed to sending an astronaut to the moon by the end of the decade, but had little experience with human spaceflight. Aerospace measurements of space radiation revealed potential hazards for astronauts traveling through certain regions of space, but also indicated that if these regions were avoided, the hazards were manageable. Aerospace studies also determined that a properly hardened spacecraft could operate for many years in the space environment. For the most part, the early Aerospace research provided information that was entirely new in the field of space physics, although some of it served to confirm or extend earlier findings.

Bruce H. Billings took over as head of Laboratory Operations following Sherwin’s departure in April 1963. Meanwhile, Becker continued to direct the Space Physics Laboratory, guiding its course

through the mid-to-late 1960s. By the end of 1963, the lab was assisting the Air Force with the Manned Orbiting Laboratory (MOL), a program that would increase in importance at Aerospace throughout the decade. Even though the MOL program was not formally approved by President Lyndon Johnson until 1965, Billings noted in his first Quarterly Technical Report in February 1964 that all of the laboratories were involved in preliminary studies of “the various types of experiments that can be done in the Manned Orbiting Laboratory.” The MOL program was of particular interest to the Space Physics Laboratory, because, as Billings noted, “knowledge of the space environment is certainly a requirement for any military space operation.” Laboratory personnel were involved with the series of experiments scheduled for the Air Force astronauts onboard MOL, as it was believed that there were “many areas where the presence of a man can vastly facilitate the collection of space environmental data.” Programs to support MOL included ground-based and space-based observations of the sun, studies of solar activity, and studies of x-ray emissions from the sun. Participating in this work were Mayfield, Vrabc, Hugh Rugge, Arthur Walker, and Ernest Rogers.

Also in 1964, two previously planned projects came to successful conclusions. A series of experiments dealing with space radiation were flown on a Discoverer satellite, which also carried several experiments designed to characterize the infrared and ultraviolet backgrounds of Earth. These backgrounds needed to be understood so they could be filtered out by any proposed missile-launch detection systems. In addition to these discoveries, Mayfield, Vrabc, and Richard Hall designed an advanced interferometer, which helped usher in the new field of far-infrared spectroscopy.

Payload capacity gradually increased in the mid-1960s, and researchers enjoyed a shorter waiting period to get their experiments into orbit. The increase in payload size, together with the Air Force’s acceptance that some payloads could be used for pure research, enabled the laboratory to expand the number of its onboard experiments. Beginning in 1965, Aerospace was also assisted by the Air Force Space Systems Division’s Space Experiments Support Program, which was created, in part, to match experiments with available satellite payload space. The program clearly

demonstrated the Air Force's recognition of the practical benefits of Aerospace research. Billings remarked that the growing awareness of the need for these experiments was "increasing the stature of our Space Physics Laboratory and increasing their usefulness to Aerospace and [the Space Systems Division]."

Additional research between 1964 and 1966 helped expand the space radiation knowledge base. Experiments mounted on P-11, a small radiation-measuring satellite instrumented by the laboratory, returned a steady stream of data that enabled Aerospace scientists to measure high-energy proton spectra over a wide portion of the outer radiation belt. The laboratory also participated in the Space Systems Division Satellite Survivability Program, which was initiated to determine the survival chances of a satellite that had been exposed to radiation from a nuclear device. In 1966, as part of its ongoing support for MOL, the lab was assigned to study the hazards that solar flare particles might cause for astronauts.

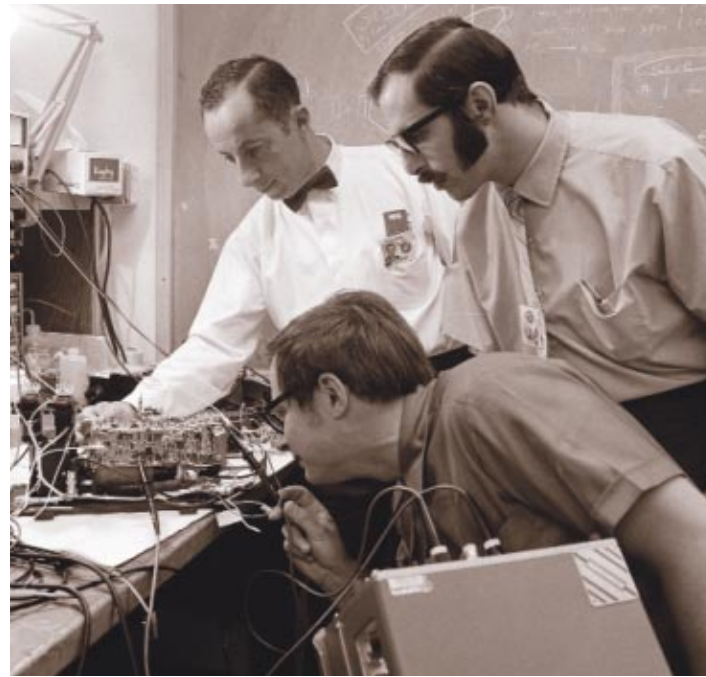
The years 1967–1968 witnessed the continuation of what Billings called the "frantic pace" of work in the Space Physics Laboratory. The first NASA Advanced Technology Satellite, launched in December 1966, carried an Aerospace experiment, and it continued to return data for several years. This satellite provided the first opportunity to study a radiation belt in a synchronous orbit and helped Aerospace scientists ascertain the hazards posed by radiation to various detector systems.

The Solar Perturbation and Atmospheric Density Experiments Satellite (SPADES) with nine experiments onboard was successfully launched into a polar orbit on July 11, 1968. According to Gilbert King, vice president of the laboratories at the time, SPADES was "the most elaborate satellite ever orbited by the [Air Force] Office of Aerospace Research." It was conceived to help the Air Force Space and Missile Systems Center better predict the ephemerides of satellites at low altitudes. The laboratory in 1968 also participated in projects to develop sensors for Project 949, a satellite to detect nuclear explosions and missile launches. Aerospace was assigned the task of completely redesigning the nuclear-burst detection package for the program's second block of satellites. The research for this work was completed that year, and the results filled a four-volume study.

Administrative changes affected the laboratory in 1968. In August, Becker was promoted to associate general manager of laboratories, and George Paulikas, who had served as head of the laboratory's particles and fields department, became the laboratory's new director. Department heads were Blake, particles and fields; Mayfield, solar physics; Rugge, laboratory aeronomy; and Elliott, space radiation and atmospheric.

The laboratory continued its involvement in a variety of pathbreaking projects as the end of the 1960s approached. Because 1969–1970 was a period of maximum solar activity, members of the laboratory spent a good deal of time at Aerospace's San Fernando Observatory, which was dedicated on February 19, 1969. The observatory, built at the Van Norman Reservoir near Sylmar, California, was part of the Space Physics Laboratory. One of the observatory's missions was to support the MOL program with investigations of the active regions of the sun that contribute to changes in the space environment. Although MOL was canceled in the summer of 1969, important data on the evolution of active solar regions were gathered at the observatory, which continued as an important source of solar observations until 1976. In the related area of "space weather," T. Y. Chiu made an important contribution through his studies of gravity waves. Chiu solved the differential equation for wave propagation in the upper atmosphere, thereby contributing to the operational procedures of controlling satellites.

By 1970, the reputation of the Space Physics Laboratory was solidly established after only 10 years of operations. In April, laboratory personnel were called upon to assist NASA with the return of the crippled Apollo 13 spacecraft because of their "extensive knowledge of the inner radiation belts." Aerospace data confirmed that the thin-skinned Lunar Module could safely travel through the radiation belts, thereby relieving "considerable apprehension" at NASA about earlier, short-term readings from instruments flown aboard Apollo 12.



A model of an inner radiation belt Cerenkov counter is tested by Samuel Solow, Norman Katz, and W. A. Kolasinski (seated).

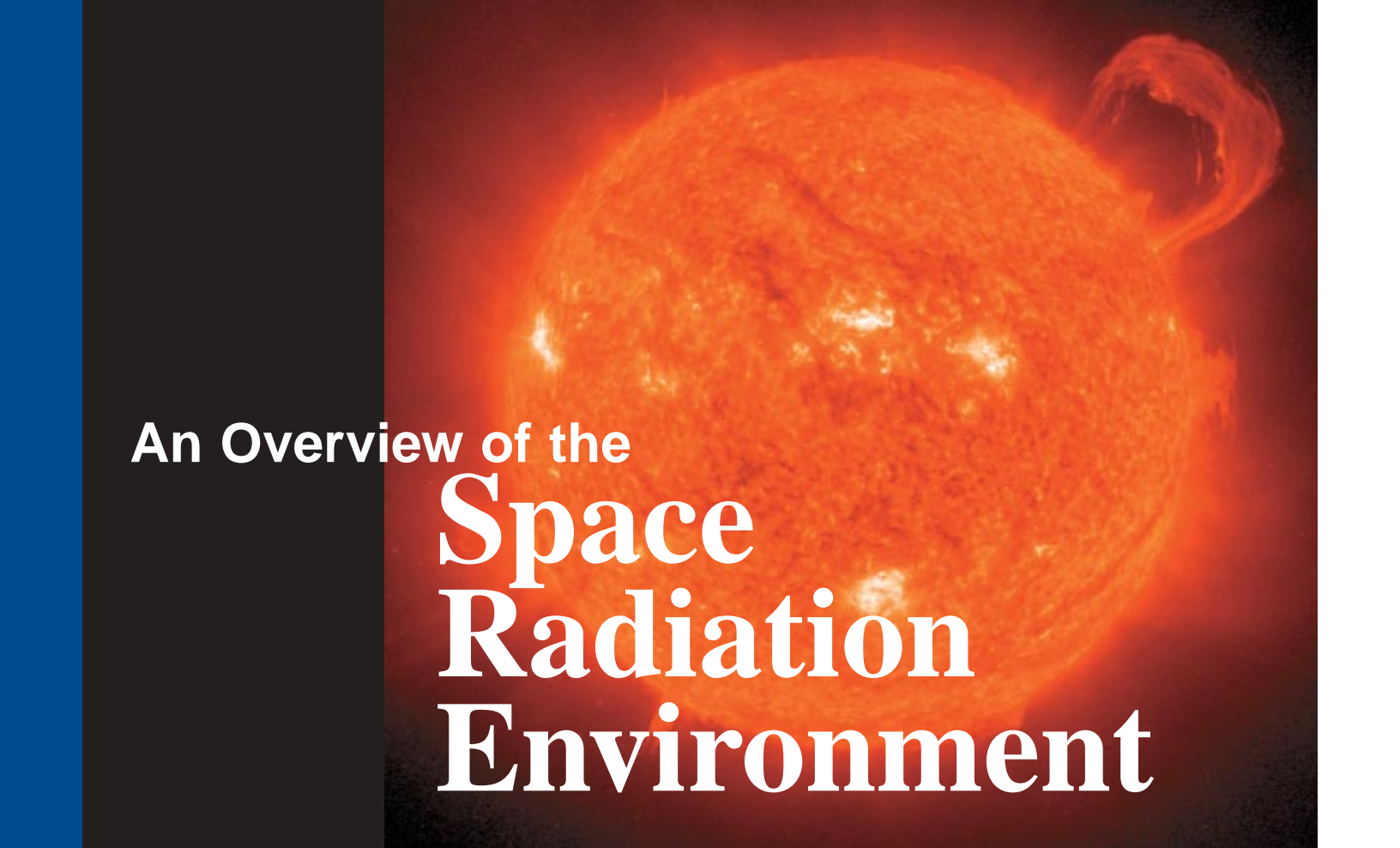
In a very different project, the laboratory conducted a study for the U.S. Department of Transportation in 1970 to determine whether the planned supersonic transport would change the ozone concentration in the stratosphere and lead to enhanced ultraviolet radiation at Earth's surface.

Robert Becker wrote in a 1970 report that the great respect that the laboratory had so quickly gained in scientific circles resulted from its "decade of observations from space." By that time, the laboratory had conducted experiments on 30 NASA and Air Force satellites and listed among its many achievements the first identification of solar electrons over the polar regions, the collection of detailed data of the radiation environment in the range of synchronous orbit, the formulation of dynamic and predictive models of the upper atmosphere, and the first satellite measurements of atmospheric density at altitudes below 275 kilometers. Getting noted in his memoirs that "much of the work done at Aerospace was at the frontiers of science"; clearly, that describes the early research work of the Space Physics Laboratory.

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# An Overview of the Space Radiation Environment

*Space systems operate in an environment whose effects and descriptions are unusual compared with the weather in Earth's atmosphere.*

*Engineering new systems to survive and perform in space is still a challenge after more than 40 years of spaceflight.*

**J. E. Mazur**

**S**pace systems operate in conditions that are much different from terrestrial weather. The space environment, just as any environment on Earth, contains phenomena that are potentially hazardous to humans and technological systems; however, many of these hazards involve plasmas and higher-energy electrons and ions that are relatively uncommon within Earth's atmosphere. The description of the space environment requires new terminology for both the hazards and the places they occur. These hazards exist in broad spatial regions that change with time. Typical satellite orbits cross many of these regions and spend a variable amount of time in each.

The space environment is populated with electrons and ionized atoms (ions). The unit of kinetic energy for these particles is the electron volt. At high energies (millions of electron volts), these particles have sufficient energy to ionize atoms in materials through which they propagate. At lower energies (below thousands of electron volts) their effects range from charge accumulation on surfaces to material degradation.

The interaction of space particles with spacecraft materials and electronics is complex to describe and difficult to simulate with ground-based test facilities. It is also not possible to fully specify the space radiation environment for a given mission because of unknowns in mapping it and unknowns in the processes that generate it. The space environment also changes with time, often in unpredictable and undiscovered ways, making it a challenge to completely assess the hazards in any orbit.

### **Interplanetary Space**

The sun and most planets in the solar system generate magnetic fields. The space outside the local effects of planetary magnetic fields contains its own population of particles. Several satellites near Earth continuously monitor the intensity of the particles and electromagnetic fields in interplanetary space. These and other space probes have shown that the radiation environment in the solar system is highly variable, but the consistent locations of intense radiation are the planetary magnetospheres.

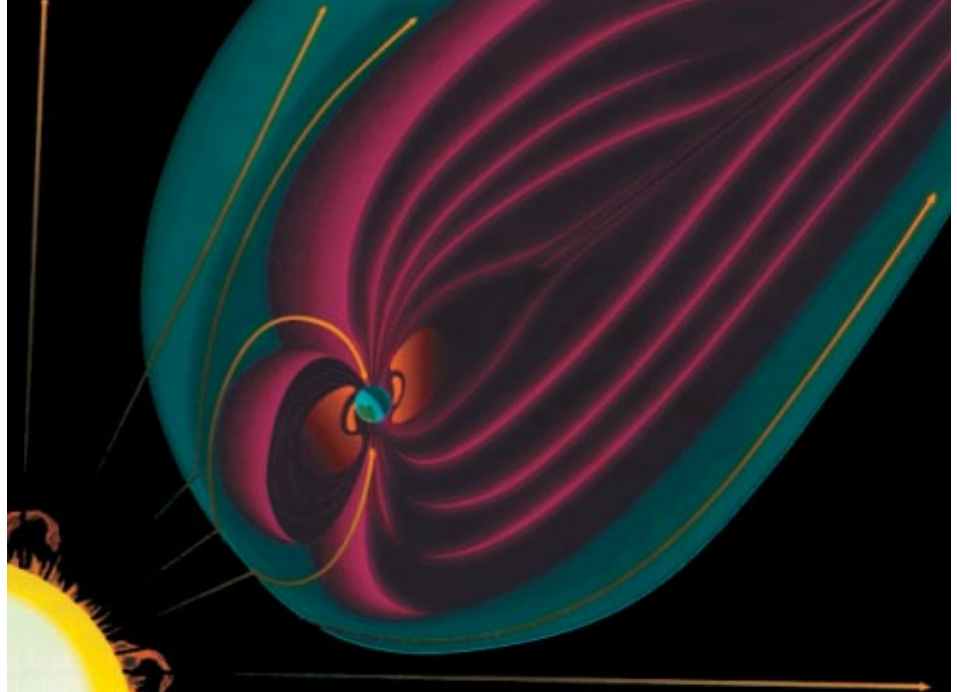
The space between the planets is not a vacuum, but at about 10 particles per cubic centimeter, the particle density is many orders of magnitude below typical densities of materials found on Earth.

However, what counts for radiation effects is not only the particle density, but also how the energy is distributed among the particles. By combining measurements from a large number of space particle instruments as well as ground-based detectors, researchers have shown a tremendous range in both particle intensity and energy, with fewer and fewer particles at higher and higher energies.

### Solar Wind

Most of the particles in interplanetary space are in the form of a hot, ionized gas called the solar wind; it flows radially from the sun with a speed at Earth that varies from about 300 to 1000 kilometers per second, representing a mass loss of about  $10^{14}$  kilograms per day. The mechanism that heats the upper solar atmosphere to roughly 1 million degrees is intimately linked to the creation of the solar wind. The heating mechanism is unknown, but may originate in constantly reorganizing magnetic fields. X-ray images of the solar atmosphere at low altitudes show regions of varying intensity. The brightest and hottest regions, with temperatures at several million degrees, lie above sunspots. The darker areas are coronal holes—large, cooler volumes of the atmosphere filled with magnetic field lines that extend into interplanetary space. In the coronal holes, the solar wind travels about twice as fast as it does from regions on the sun with magnetic fields that loop back to the surface. Coronal holes can last many solar rotations and will be the dominant feature in the solar atmosphere from 2003 to 2005, when the sun approaches its activity minimum.

Explosive ejections of large volumes of the solar atmosphere, known as coronal mass ejections, draw out complex loops of magnetic field into interplanetary space.



Earth's magnetosphere is a teardrop-shaped cavity formed by the interaction of the solar wind (gold) with Earth's magnetic field. The solar wind becomes subsonic at the bow shock (blue). The magnetosphere contains the Van Allen radiation belts (orange) and other particle populations.

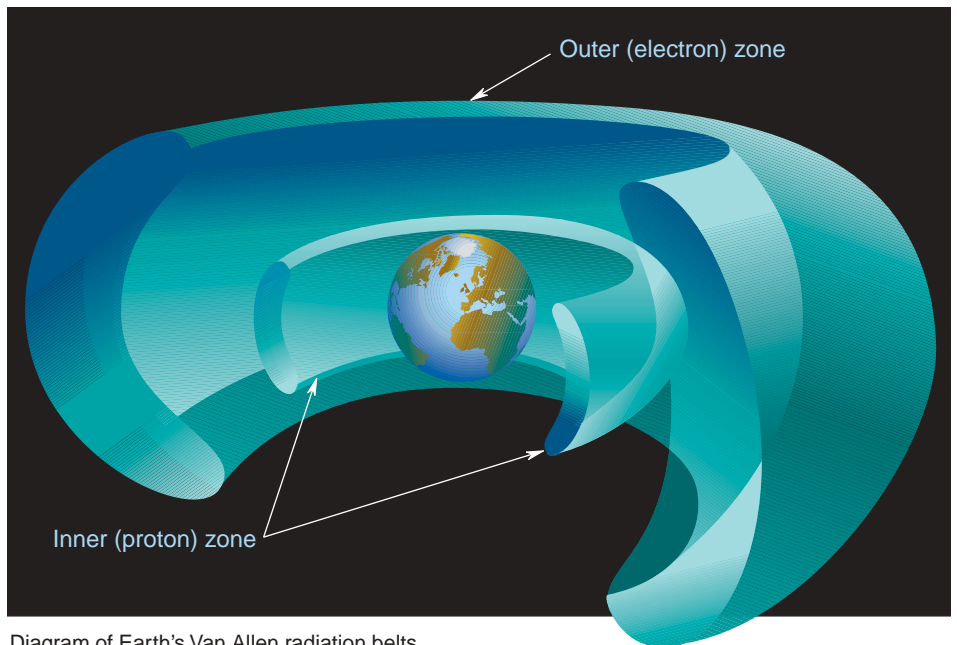
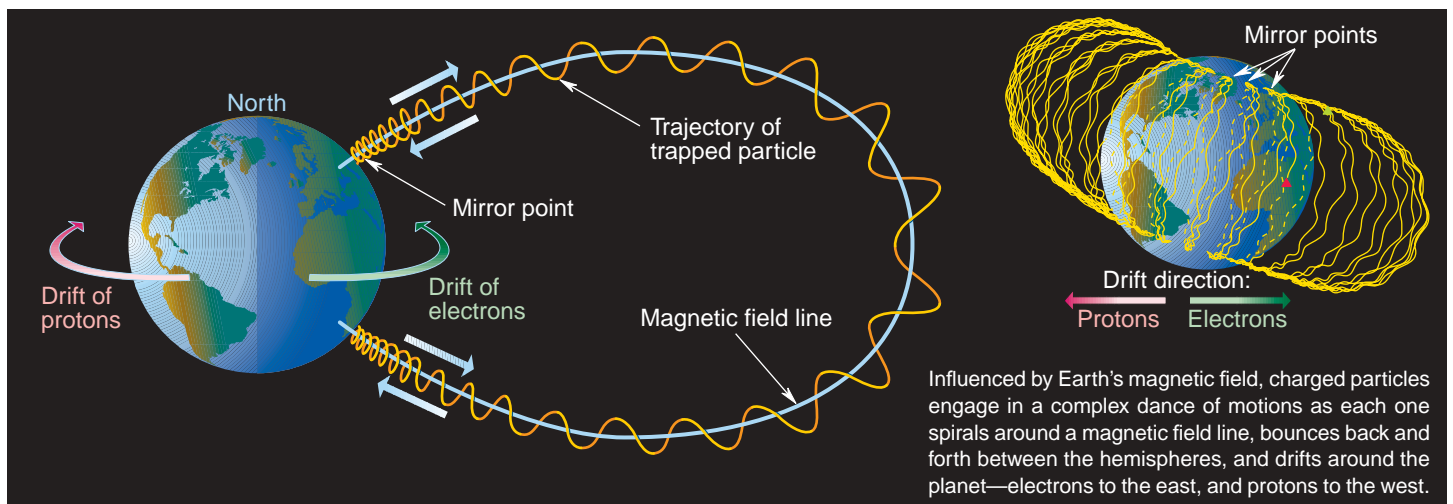


Diagram of Earth's Van Allen radiation belts.



The magnetic field's direction and strength determine how energy from the solar wind gets transferred into the planetary magnetospheres.

### Solar Energetic Particles

Many highly variable sources produce interplanetary particles with energies typically between 10 thousand and 100 million electron volts. These energetic particles originate in acceleration processes in the solar atmosphere, sometimes close to the sun and sometimes beyond Earth's orbit. The transient nature of these particle populations is directly linked to the sun's activity.

An increase in solar energetic particles is only one manifestation of a complex sequence of events that begins with a large energy release at the sun. While these energy releases are generally called "proton events," and it is true that protons are the most abundant ion produced, these events also energize ions as heavy as iron. Both the protons and the heavy ions are hazardous to spacecraft: The more abundant protons are primarily responsible for anomalies resulting from the total radiation dose, while heavy ions contribute most to anomalies known as single-event effects.

### Galactic Cosmic Rays

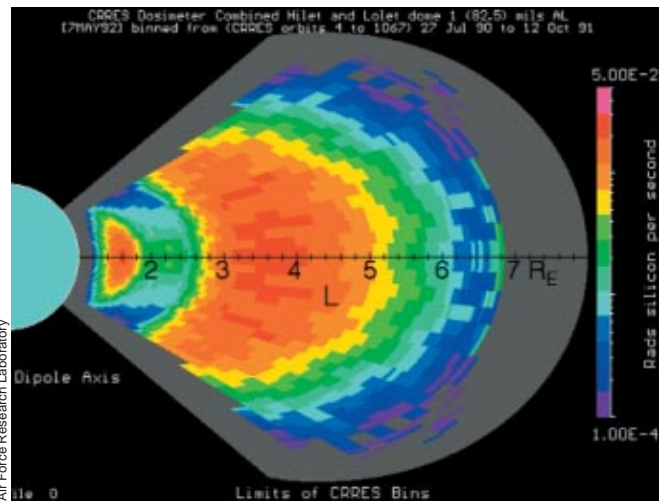
Galactic cosmic rays are the highest-energy particles in the solar system—even Earth's magnetic field is usually not sufficient to deflect them. They originate somewhere outside the solar system (possibly in supernova shocks) and probably represent the accumulated output of many particle

sources and acceleration processes. Always present at Earth, they consist of about 87 percent protons, 12 percent helium nuclei, and 1 percent heavier ions.

During several years around solar maximum, the sun is more likely to eject disturbances into interplanetary space. As these disturbances propagate, they carry tangled magnetic fields that scatter the lowest-energy galactic particles. Hence, the galactic particle intensity at Earth varies inversely with the solar cycle (it also varies with radial distance from the sun and latitude above the ecliptic plane, although these effects are small compared to the solar cycle variations). Because of the solar cycle, one might even consider a long-duration mission to Mars at solar maximum rather than at solar minimum because the galactic radiation—which is impossible to shield against—is at lower levels during solar maximum.

### Earth's Magnetosphere

Earth's magnetic field establishes a volume of space within which the magnetic field dominates charged particle motion. Close to Earth, the magnetic field is roughly a magnetic dipole that is tilted 11.5 degrees



Measured radiation dose versus distance from Earth reveals the inner and outer radiation belts.

from the rotational axis and offset from the center of the planet. For most purposes, the dipole approximation is poor, and there are more sophisticated models that account for the steady changes of the central field as well as the dynamic outer boundaries.

The magnetosphere is complex and dynamic because of its interaction with the variable solar wind and transient phenomena from the sun. On the sunward side, the magnetosphere extends about 10 Earth radii (roughly 60,000 kilometers). On the opposite side, the magnetotail extends beyond 200 Earth radii. The sunward dimension can change by more than a factor of two depending on the interplanetary magnetic field and solar wind upstream from Earth.

The magnetosphere contains a mixture of plasmas with incredibly diverse sources. Some populations of charged particles are trapped within the magnetosphere while others vary on many time scales. The magnetosphere has its own weather, with complex processes of particle transport and acceleration during geomagnetic storms that contribute to surface charging and internal charging of spacecraft.

A charged particle in a constant magnetic field experiences a force perpendicular to its motion. The resulting trajectories of ions and electrons in the magnetosphere are a complex superposition of motions as each particle travels in a spiral around a magnetic field line, bounces back and forth between the North and South Poles, and drifts around the planet, with electrons drifting east and protons drifting west.

Stable trapping of particles occurs, given the right combination of particle charge, energy, and magnetic field strength. As

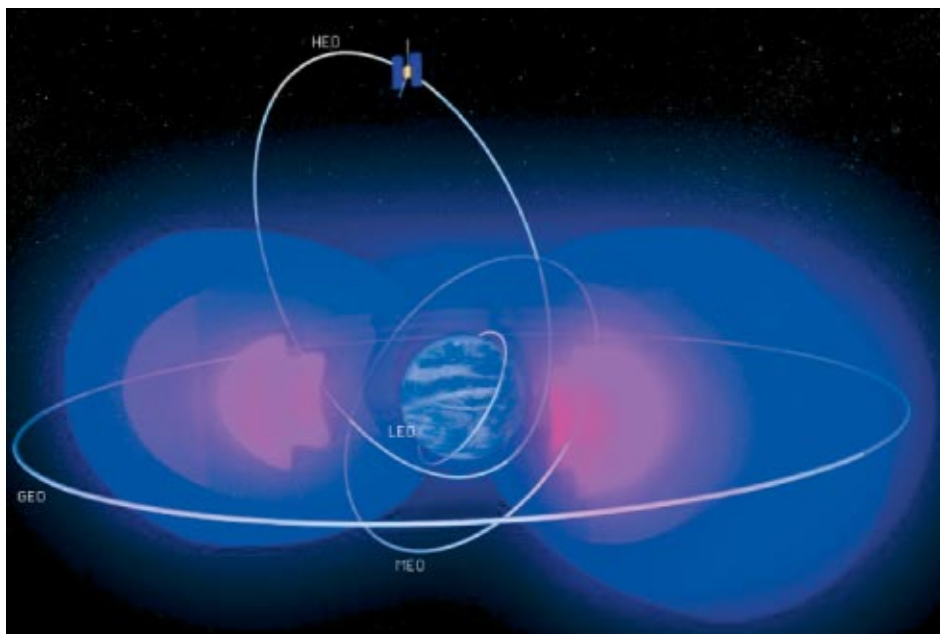


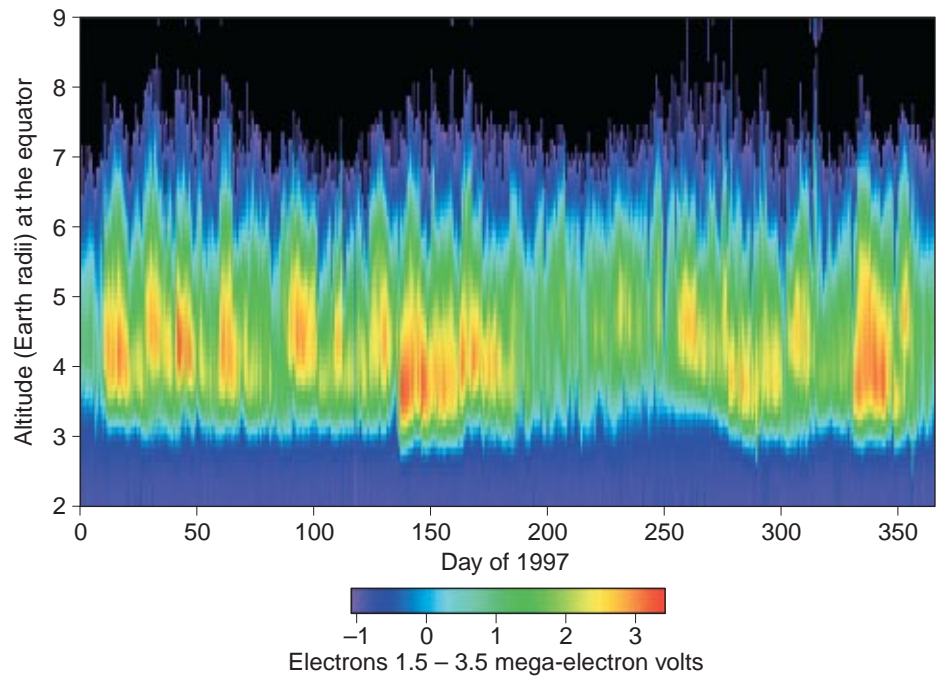
Illustration by B. Jones, P. Fuqua, J. Barrie, The Aerospace Corporation

The Van Allen radiation belts and typical satellite orbits. Key: GEO—geosynchronous orbit; HEO—highly elliptical orbit; MEO—medium Earth orbit; LEO—low Earth orbit.

these particles are trapped on time scales ranging from days to years, they execute their gyration, bounce, and drift motions around Earth, resulting in spatial zones of trapped radiation known as the Van Allen belts. The inner zone is the proton belt (peak intensity at about 3000 kilometers from Earth's surface) and the outer zone the electron belt (peak intensity from about 12,000 to 22,000 kilometers from the surface).

There are trapped electrons and protons throughout the magnetosphere, but the division into two zones is reasonable because the radiation dose from trapped particles is usually highest in these regions. Also, the particles that contribute most to the radiation dose in the inner zone are protons and those contributing most in the outer zone are electrons. Occasionally, new radiation belts form between the inner and outer zones when interplanetary shock waves from coronal mass ejections hit the magnetosphere.

Different processes produce and sustain the proton and electron belts. Galactic cosmic rays collide with atoms in Earth's atmosphere and produce showers of secondary products. Some of these products are neutrons that subsequently decay into energetic protons; thus, cosmic rays are the most important source of energetic particles in the inner zone. The telltale clue for the decay source is the dominance of protons over other types of ions. Another clue is the relative stability of the inner zone, which results from a combination of long particle lifetimes in this part of the



Typical variability of outer-zone electron intensity measured from low Earth orbit on the NASA/SAMPLEX satellite, shown for the entire year 1997. The intensity is the logarithm of the electron count rate.

magnetic field and the slowly varying cosmic ray input.

The offset of Earth's magnetic dipole from the geometric center of the planet causes a weaker field region over the South Atlantic Ocean and an opposing region of stronger field over northern Asia. As the trapped inner-zone particles execute their bounce motion along field lines, they can reach lower altitudes at a region known as the South Atlantic Anomaly. All spacecraft in low Earth orbit penetrate the inner zone

in the South Atlantic Anomaly even if their altitude is below the belt at other positions in the orbit.

While relative stability is one key property of the inner zone, variability is the outstanding characteristic of the outer radiation belt. The solar wind and interplanetary magnetic field affect this weaker field region of the magnetosphere more than the inner zone, leading to shorter lifetimes of trapped particles and more dynamics. Details of how the magnetosphere accelerates electrons to millions of electron volts in a few seconds have been recently glimpsed; however, the mechanism that accelerates the electrons more routinely in geomagnetic storms has not been established even after 40 years of research. Observations over many years with well understood space environment instruments will be needed before researchers can understand the outer zone's variability and its extreme behavior.

### Examples of Current Research

Several factors continually press the need for a better specification and understanding of the space environment. One is the increase in spacecraft lifetimes, leading to questions about longer-term exposures than have been tested in the past. Another is the growing interest in uncommon orbits, where the residence time in different hazard areas is unlike what has been experienced. A third is the use of new materials, which need to be assessed for suitability in

## Space Environment Impacts

Has the space environment ever had an impact on a mission? Is there really a clear need to measure the environment and to understand its extremes?

To answer these questions, Aerospace compiled and analyzed a database of hundreds of spacecraft anomalies that were attributed to the space environment. The survey included commercial, scientific, and other satellites, both foreign and domestic. Most spacecraft do not have onboard environmental sensors, so the role of the environment in any anomaly is usually not clear and requires expert assessment. This is a common problem: The space environment can be extremely localized in its effects, and other hardware problems might mimic the effects caused by space hazards. Nevertheless, this study presented some intriguing data.

The Aerospace survey found that effects from electrostatic discharge were responsible for more than half of all anomalies. Problems arising from single-event effects and total-dose radiation damage together accounted for roughly one-third of all cases. The easiest way to quantify the impact of these anomalies is by gauging the time it took spacecraft operators to recover normal operations. Most anomalies affected users for one hour to one day or for more than a week. Some mission failures were also attributed to the space environment, mostly through the effects of electrostatic discharge from surface charging.

Even within the limitations of the survey, it was clear that the environment has had an impact on space systems; however, it is not possible to predict its effects on future space systems, which may involve relatively unexplored orbits, new technologies, new materials, and evolving engineering practices.

Space hazard	Spacecraft charging		Single-event effects			Total radiation dose		Surface degradation		Plasma interference with communications	
	Surface	Internal	Cosmic rays	Trapped radiation	Solar particle	Trapped radiation	Solar particle	Ion sputtering	O <sup>+</sup> erosion	Scintillation	Wave refraction
LEO <60°	Not applicable	Not applicable	Relevant	Important	Not applicable	Important	Relevant	Relevant	Important	Important	Important
LEO >60°	Relevant	Not applicable	Important	Important	Important	Important	Relevant	Important	Important	Important	Important
MEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GPS	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
GTO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GEO	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
HEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
Inter-planetary	Not applicable	Not applicable	Important	Not applicable	Important	Not applicable	Important	Relevant	Not applicable	Relevant	Relevant

Important
  Relevant
  Not applicable

Space environment hazards for typical orbits. Key: LEO <60°—low Earth orbit, less than 60 degrees inclination; LEO >60°—low Earth orbit, more than 60 degrees inclination; MEO—medium Earth orbit; GPS—Global Positioning System satellite orbit; GTO—geosynchronous transfer orbit; GEO—geosynchronous orbit; HEO—highly elliptical orbit; O<sup>+</sup>—atomic oxygen.

space. Aerospace has been conducting research to address the concerns raised by these and other issues.

### Plasma Effects on Surfaces

Space plasmas can change the physical properties of exposed surfaces. For example, optical coatings are used to increase the efficiency of solar arrays; their performance depends in part on their transmittance, which can change after a long exposure to the space plasma environment.

Aerospace is beginning to derive preliminary specifications of the low-energy plasmas around Earth based on data from previous and active science missions. As is often the case, instruments designed in the past were not optimized to answer new questions and suffer from a lack of sensitivity and coverage in the orbits of interest. These new questions pose a challenge as researchers try to quantify and understand a relatively unexplored regime of space particles.

### Extreme Value Analysis

The highest intensity of outer-belt electrons in the past 16 years occurred in a geomagnetic storm on March 28, 1991. One question important for space systems design is whether a similar or more intense event will occur during a future mission.

Aerospace has used mathematical tools known as the statistics of extreme events to help answer this question. The analysis indicates that the March 1991 event was equivalent to a 20-year storm, so the likelihood is high that a storm of that intensity and duration could take place in the next few years. In fact, the period from about 2003 to 2005 will have intense outer-belt events because high-speed solar winds usually occur during the upcoming phase of solar activity. The analysis also suggests that a 100-year storm could be about twice as intense. This mathematical approach does not predict when such events will occur, but it has potential to specify the extreme environment, thereby satisfying an important engineering requirement.

### Future Needs

Just as every terrestrial flood or hurricane is different, so too are the events in the radiation environments of Earth and interplanetary space. Averaging the rainfall in southern Florida can reveal long-term weather trends, but could never describe the effects of a single hurricane. Similarly, a multiyear average of the intensities in Earth's electron radiation belt reproduces the average environment appropriate for a total-dose estimate, but could never describe a single

geomagnetic storm. Longer-duration missions with more capable instrumentation, augmented with more precise theories of space environment phenomena, will help designers specify the environment better and characterize its extreme events more accurately as well.

Space systems must meet their performance requirements regardless of the space weather, so the specifications that affect the engineering on the ground are crucial to their success. This is especially true as mission planners explore the use of different orbits, new materials and technologies, and longer satellite lifetimes. Thus, more support is needed for the development of new space environment specifications and models based on modern and more comprehensive data sets.

Current missions are expanding databases of measurements of trapped radiation, Earth plasmas, solar energetic particles, and galactic cosmic rays. The combination of better data and theories will yield better models, but the models will only be useful to the engineering of space systems if their focus from the start is on their application to actual missions.

### Acknowledgements

The author would like to thank P. C. Anderson, J. B. Blake, M. W. Chen, J. F. Fennell, H. C. Koons, M. D. Looper, T. P. O'Brien, J. L. Roeder, and R. S. Selesnick for their contributions to this overview.

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# What Could Go Wrong?

## The Effects of Ionizing Radiation on Space Electronics

John Scarpulla and  
Allyson Yarbrough

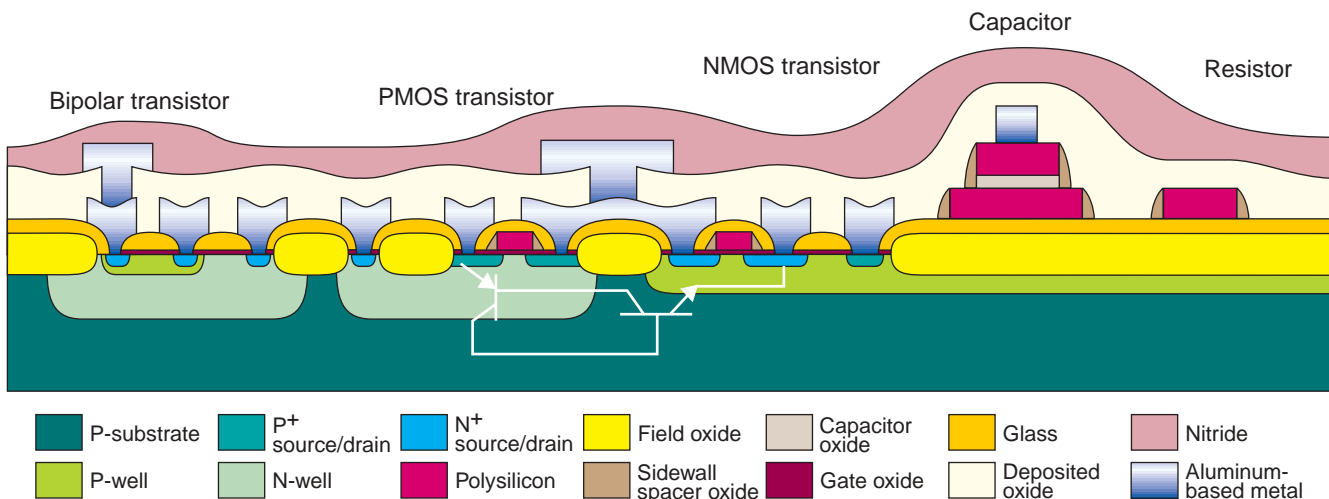
*Space radiation comes in many forms and affects electronic components in diverse ways. Aerospace investigations of how energetic particles interact with integrated circuits and other electronics have been helping spacecraft designers and mission planners minimize the risk of component failure or performance degradation.*

The harsh space environment can wreak havoc on unprotected electronics. Over time, exposure to energetic particles can degrade device performance, ultimately leading to component failure. Heavy ions, neutrons, and protons can scatter the atoms in a semiconductor lattice, introducing noise and error sources. Cosmic rays speeding through space can strike microcircuits at sensitive locations, causing immediate upsets known as single-event effects. Passive electronic components and even straightforward wiring and cabling can be seriously affected by radiation. Aerospace has been investigating the means by which heavy ions, protons, and electrons interact with microelectronics. This effort has helped spacecraft designers find ways to prevent serious anomalies on orbit.

A typical integrated circuit contains various elements such as capacitors, resistors, and transistors embedded in a silicon substrate and connected by metallic vias (holes that allow electrical connections between front-side metal and

the back-side ground plane or between planes in a multilayer structure). These elements are separated by dielectrics and covered by protective layers of passivating insulators and glass. Problems arise when space radiation subverts the normal function of these components or bridges the isolation between them.

Various types of semiconductors are used in microelectronics. For example, the negative metal-oxide semiconductor (NMOS) transistor operation is based on the flow of negatively charged electrons. The positive metal-oxide semiconductor (PMOS) transistor operates based on the flow of positive charges, carried by so-called “holes” (a “hole” is the absence of an electron, or a missing bond that can hop from atom to atom like a positive charge carrier). The complementary metal-oxide semiconductor (CMOS) employs both of these on the same chip. CMOS technology is commonly found in digital circuits such as microprocessors and memories, analog circuits such as operational amplifiers and phase-locked loops,



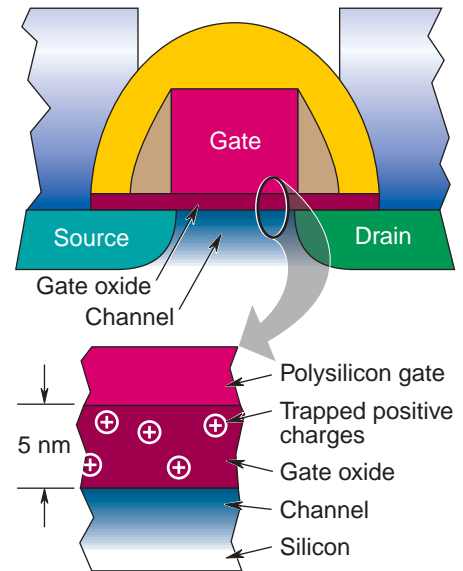
partial cross section of a typical silicon CMOS integrated circuit. Only one metallization layer is shown for simplicity (an actual circuit may have many more). In this figure, eight different p-n junctions (positive-negative, denoting the polarity) are visible; in a real integrated circuit there may be thousands or even millions. The cross section shows a

bipolar transistor implanted in an n-well, a PMOS transistor in the same n-well, an NMOS transistor in a p-well, a polysilicon-oxide-polysilicon capacitor, and a polysilicon resistor. Radiation effects differ in each device even though they may be located in close proximity. Short circuit paths that cause latchup are also shown.

## Radiation Dosimetry

When energetic particles enter a target material, they ionize some of the atoms of the target by breaking bonds. This requires energy, between 2 and 20 electron volts per bond depending upon the material (the electron volt, or eV, is a unit of energy;  $1 \text{ eV} = 1.602 \times 10^{-19}$  joules). The ability of the radiation to deposit energy per unit mass of the target material is defined as the "radiation dose." It is expressed in grays, or Gy (in honor of Louis Harold Gray, 1905–1965, the British physician who was an authority on the use of radiation in the treatment of cancer). One gray equals 1 joule of deposited energy per kilogram of the target material. An older, similar unit, still in widespread use, is the rad (radiation absorbed dose), which is equal to 100 ergs per gram. One gray equals 100 rads. It is also customary to define the target material (e.g., Gy(Si) in the case of silicon) because different materials have different abilities to absorb energy from a given radiation field.

Another common unit is the roentgen, a unit of exposure, rather than dose. This unit is named for Wilhelm Roentgen (1845–1923), the first Nobel laureate in physics and the discoverer of the x ray. For x rays and gamma rays, which are forms of electromagnetic radiation, exposure is defined as the ability of the radiation to produce ionization charges in air. One roentgen is defined as 1 electrostatic unit, or esu ( $\frac{1}{3} \times 10^{-9}$  coulomb) per cubic centimeter of dry air at standard temperature and pressure. The measurement of gamma-ray or x-ray dose can be performed using an electrometer type of ionization detector, which directly measures this charge. A conversion from exposure to dose is straightforward, however it is material dependent.



Cross section of an NMOS transistor showing the gate oxide and conducting channel formed between the source and drain. The trapped charges shown in the inset are responsible for the threshold voltage shift, ultimately leading to failure.

and mixed-signal devices such as analog-to-digital converters. All of these components are generally found aboard a spacecraft.

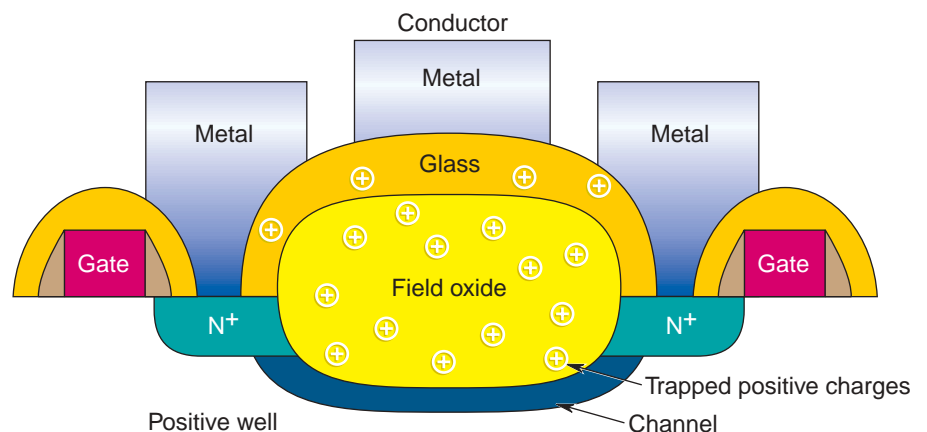
### Total Dose Effects

Total dose refers to the integrated radiation dose that is accrued by satellite electronics over a certain period of time, say 1 year, or over a 15-year satellite mission. The radiation has the capability to damage materials by virtue of its ability to ionize material. The energetic ions then can cause damage to materials by breaking and/or rearranging atomic bonds. In general, after exposure to sufficient total-dose radiation, most insulating materials such as capacitor dielectrics, circuit-board materials, and cabling insulators become less insulating or become more electrically leaky. Similarly, certain conductive materials, such as metal-film resistors, can change their characteristics under exposure to total-dose radiation. The metal conductors themselves and magnetic materials tend to be quite radiation hard or resistant to radiation effects. Semiconductor devices in particular exhibit a number of interesting effects. It is important to choose materials and components for satellite electronics that have the necessary radiation tolerance for the required mission. It is also necessary to design in margins or allowances for the expected component changes induced by the radiation environment.

Perhaps the most ubiquitous component in modern microelectronics is the MOS

transistor. Coincidentally, it also can be particularly sensitive to radiation. The MOS transistor is an active component that controls the flow of current between its source and drain electrodes. Commonly used as a switch in digital circuits, it may be open or closed depending on whether a voltage is supplied to its control gate electrode. For example, when sufficient voltage is applied to the gate of an NMOS transistor, it allows current to flow; when the voltage remains below the critical threshold, the gate does not permit current to flow. The threshold voltage depends upon the device design and the materials used, but is usually 0.5 to 1.5 volts. The gate oxide, which isolates the gate from the source and drain, is an ideal insulator made of silicon dioxide.

Problems arise when this device is exposed to radiation. First, the gate oxide becomes ionized by the dose it absorbs. The free electrons and holes drift under the influence of the electric field that is induced in the oxide by the gate voltage. These holes and electrons would be fairly benign if they were to simply drift out of the oxide and disappear, but although the electrons are fairly mobile, the holes are not, and a small fraction of them become trapped in the gate oxide. After sufficient radiation dose, a large positive charge builds up, having the same effect as if a positive voltage were applied to the gate. With enough total dose, the device turns on even if no control voltage is applied. The transistor source-drain current can no longer be controlled by the gate, and remains on permanently.



A region of field oxide between two isolated NMOS transistors. When the field oxide traps radiation-induced charges, a conduction channel forms between the two transistors, destroying the isolation.

The PMOS transistor exhibits a similar, but opposite, effect. When no voltage is supplied, the gate allows current to flow; when the voltage crosses a critical threshold, the gate prevents current from flowing. Therefore, when radiation traps enough positive charge in the gate oxide, the transistor remains off permanently. In a CMOS logic gate consisting of NMOS and PMOS transistors, the output will be frozen at either a “1” or a “0” after a sufficient dose is accumulated, and the device will cease to function.

Some integrated circuit manufacturers have tried to produce transistors with gate oxides that are “hard”—that is, they do not trap positive charges upon radiation exposure. These products can tolerate total-dose levels as high as 1 megarad without difficulties, making their use possible in satellite systems for many years. On the other hand, many commercial products lacking a hardened gate oxide (such as the processors used in desktop computers) might last a few days or weeks in a satellite orbit.

The CMOS integrated circuit market is extremely competitive, with succeeding generations of products offering greater processing power and speed. These gains are achieved by shrinking the transistors so that more can be packed on a single chip. As a consequence, the gate oxides in these shrinking transistors are growing thinner—just a few nanometers thick for the latest generation. Being thinner, the gate oxide traps less positive charge overall. Therefore, CMOS transistors are naturally becoming more radiation resistant. Still, gate oxides are not the only features affected by total ionizing dose.

The transistors in a CMOS device are isolated or separated by so-called field regions. Two different circuits that lie near each other will commonly be separated by

Radiation environment	Shielding feasibility	Typical effects
Total ionizing dose	Some	<ul style="list-style-type: none"> <li>–Threshold shifts in CMOS transistors, leading to failure of logic gates</li> <li>–CMOS field-oxide charge trapping, loss of isolation, excessive power-supply currents</li> <li>–Power transistor threshold shifts, loss of on/off control</li> <li>–Gain degradation in bipolar-junction transistors</li> </ul>
Neutron or proton flux events	Some	<ul style="list-style-type: none"> <li>–Displacement damage effects</li> <li>–Gain degradation in bipolar-junction transistors</li> <li>–Severe degradation of charge-coupled devices, dynamic memory performance</li> <li>–Damage to photodetectors</li> </ul>
Single-event phenomena	Some	<ul style="list-style-type: none"> <li>–Single heavy ion causes ionization “track”</li> <li>–Temporary logic scramble</li> <li>–Single bit errors in static memories</li> <li>–Localized latchup in CMOS integrated circuits</li> <li>–Gate rupture of power transistors</li> <li>–Temporary upset of analog devices such as amplifiers</li> <li>–Burnout of diodes, transistors</li> <li>–Discharge of capacitors</li> </ul>

This table shows the main categories of space radiation and indicates the feasibility of shielding each type in a typical satellite. Typical effects on electronics are also described.

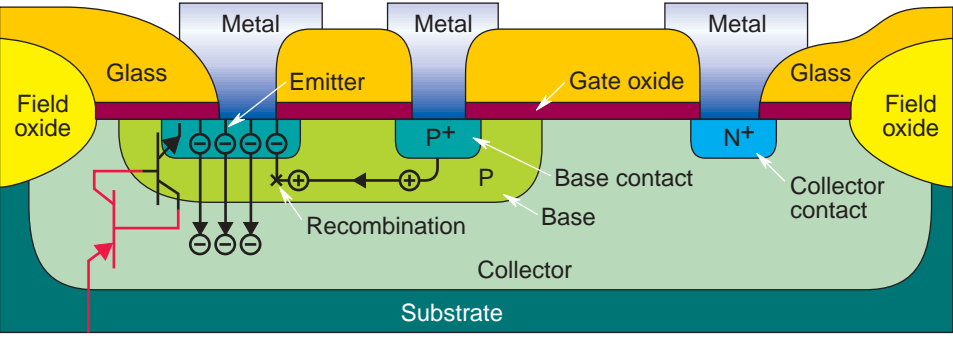
a thick field oxide and sealed by an overlying metal conductor. Just like the gate oxide, the field oxide can trap positive charges through extended exposure to ionizing radiation. If enough charge is trapped, a channel of conducting electrons will form in the silicon under the field oxide. This effectively connects the two formerly isolated logic circuits, causing them both to malfunction.

A similar effect can occur in a single transistor. Trapped charges in the field oxide form a leakage path along the edges parallel to normal conduction flow in an NMOS transistor. The silicon along these

edges forms an unwanted conduction path. In modern CMOS devices, edge leakage is frequently the dominant mode limiting the total-dose hardness of the product. After a high total dose, the transistors cumulatively leak so much current that the power supply can no longer handle the load. The power dissipation rises to high levels, and the chip fails. A hardened field oxide is required to help prevent this occurrence.

### Neutron or Proton Damage

When highly energetic neutrons or protons penetrate the crystal lattice of a semiconductor, such as silicon, atoms can get displaced through several mechanisms. For example, the incident particle can transfer some of its energy to the silicon nucleus, and if enough energy is transferred (approximately 25 electron volts), the nucleus gets knocked out of position. This is called elastic scattering, and the freed silicon atom can lose energy through ionization or by displacing other atoms. Inelastic scattering can also occur, whereby the struck nucleus absorbs the neutron or proton and then reemits it at a lower energy along with a gamma ray. This process also causes displacements. The displacements are essentially microscopic crystal imperfections



Operation of a bipolar junction transistor. Electrons are emitted at one end, diffuse through the middle material (the base), and are eventually collected. If the transistor were perfect, all the emitted electrons would be collected; however, some are lost through recombination with holes in the base.

that interfere with the orderly flow of charges from the source to the drain.

The resulting crystal lattice contains voids where the silicon atoms were knocked out of position and clusters where they came to rest. These sites, known as traps or recombination centers, respectively, can be a source of problems in some semiconductor devices.

For example, a bipolar-junction transistor functions as a current amplifier. A p-n junction is the place where a p-type material meets an n-type material. There are two types of bipolar-junction transistors—n-p-n and p-n-p—which are created by sandwiching semiconductor of one doping type between two other layers of the opposite type. The principle of operation of bipolar transistors is by charge-carrier diffusion, which is different from the MOS transistor, whose principle of operation is by drift. In an n-p-n bipolar transistor, electrons are emitted by the emitter n-type layer into a middle material known as the base, where they diffuse to the collector n-type layer at the opposite side. If the transistor were perfect, all the electrons that traverse the middle material would be collected. In actuality, some are lost through recombination with holes. The transistor gain is therefore defined as the amount of current that reaches the collector compared with the amount that recombines with the base.

When the transistor is exposed to neutrons or protons, displacement damage and new recombination centers are created. This increases the likelihood that electrons will recombine with holes in the base material. Higher neutron or proton fluxes give rise to higher rates of recombination and lower transistor gain. Eventually, the transistor fails because its gain drops too low to provide amplification. This is the dominant failure mode in bipolar integrated circuits.

Bipolar-junction transistors are also sensitive to total ionizing dose. The phenomenon is similar to that observed in MOS transistors, where an unwanted conducting channel is formed adjacent to the surfaces of the field oxide. These channels cause unwanted current that can eventually cause device failure. Similarly, MOS transistors are somewhat sensitive to displacement damage. Some of the charges are scattered by the damage sites, and the transistors exhibit a loss of conductance and an increase in noise. These degradations are themselves capable of causing circuit failures.

## Single-Event Effects

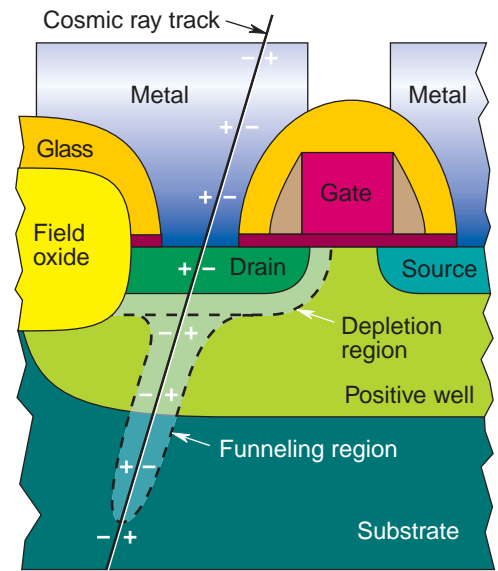
This category of radiation effects is the only one in which a single particle is the source of the trouble (see “Picosecond Lasers for Single-Event Effects Testing” and “Heavy-Ion Testing for Single-Event Effects”). Highly energetic ions such as cosmic rays can easily penetrate the structure of a spacecraft, pass through internal components, and exit the structure in a straight line. Shielding against them is simply not practical. Because the heavy particles are omnidirectional, they impinge on an integrated circuit at random times and locations, with random angles of incidence.

The concept of total ionizing dose is not useful to describe a single particle; instead, a quantity called the linear energy transfer is used. As the particle traverses the material of interest, it deposits energy along its path. Linear energy transfer is the amount of energy deposited per unit of distance traveled, normalized to the material’s density. It is usually expressed in MeV-cm<sup>2</sup>/mg. A typical satellite environment will include a wide variety of particles with various amounts of kinetic energy corresponding to a wide spectrum of linear energy transfer.

An energetic ion passes through a semiconductor device in a few picoseconds. As it does so, it leaves behind a “track” or column of ionized material typically ranging from a few tenths of a micron to a few microns in diameter. The ionized track contains equal numbers of electrons and holes and is therefore electrically neutral. The total number of charges is proportional to the linear energy transfer of the incoming particle. It is as if a conducting wire were suddenly inserted into the semiconductor device, disturbing the electric fields and normal current paths.

If a cosmic ray passes through the drain region of an NMOS transistor, a short is momentarily created between the substrate (normally grounded) and the drain terminal (normally connected to a positive power supply voltage). When this happens, a spike of current flows for an instant. The amount of charge that is “collected” from the ion track before it dissipates or disappears by recombination is significant: Every device has a certain critical charge, which, if exceeded, results in a single-event upset, burnout, or other undesirable phenomenon.

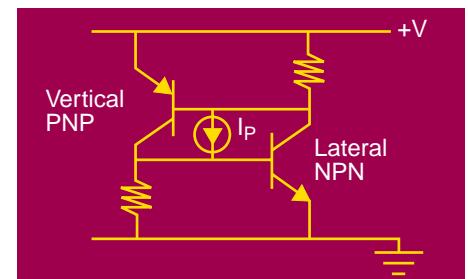
The process of energetic-ion-induced charge collection is complex and rapid, and



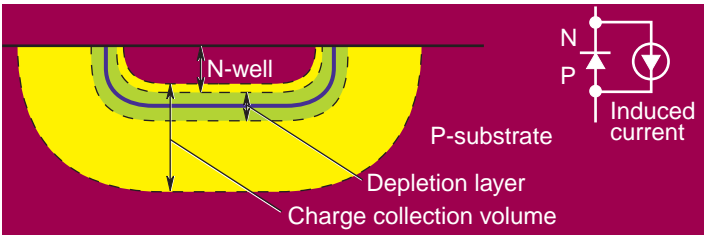
Path of a cosmic ray through the drain of an NMOS transistor. The charge liberated in the ion’s wake is collected by the funneling mechanism and through diffusion away from the junction. A short is momentarily created between the substrate (normally grounded) and the drain terminal (normally connected to a positive power supply voltage).

is not completely understood. It consists in part of charge “funneling,” where distortion of the normal electric field patterns of a device allows more charge to be collected than could normally be transported into the sensitive region. Charges are also pulled away from the drain-substrate junction by diffusion. The ability of a device to collect charge from the ion track determines its sensitivity to cosmic rays.

If a device is large, it presents a greater target for cosmic rays. It is therefore more likely to receive a “hit” than a smaller device. This relationship is described by an attribute known as the “cross section” of the device, which is calculated as the ratio of the number of single-event upsets to the



Latchup occurs when the source of one MOS transistor forges a pathway to the drain of another. A transient radiation pulse can generate the current needed to bridge this gap. Current will then continue to flow unregulated between the two components. The entire circuit must be powered down to break the connection. In some cases, the circuit may be permanently damaged.



Current is generated in a p-n junction exposed to transient radiation. It can be modeled as a transient current source in parallel with a diode.

particle flux over a given surface area. In determining the sensitivity of a device to single-event effects, two important parameters to consider are the threshold linear energy transfer, above which upsets or single events are seen, and the saturation cross section, i.e., the cross section at high values of linear energy transfer.

Researchers have identified various types of single-event effects, varying in their degree of seriousness.

A single-event transient, for example, is a temporary spike or signal caused by a heavy ion. In some cases, this spike can excite analog circuits into temporary or permanent oscillation. In digital circuits, the spike may propagate through many logic gates, causing system malfunction. In mixed-signal devices, a transient generated in the analog part of the device can propagate into the digital part, causing logic-level shifts.

A single-event upset usually manifests itself as a “bit-flip” or change of state in a logic circuit. If enough of these upsets occur, or if a single critical node is affected, a computer can freeze up and must be rebooted. Single-event upsets occur in computer memories, microprocessors, controllers, and almost any digital circuit containing latches or memory elements.

the same area of a silicon substrate, they can form a parasitic or undesired circuit element (called a thyristor) if struck by an energetic ion. A thyristor is an interconnected n-p-n and p-n-p bipolar transistor; the current amplified by the n-p-n transistor supplies the p-n-p transistor, which in turn supplies it back to the n-p-n transistor,

## Understanding how space radiation interacts with microelectronics is the first step in establishing ways to mitigate adverse effects.

creating a feedback loop. Thyristors are perfectly legitimate devices in their own right, and are used for regeneratively switching large currents. But they are, by nature, feedback devices, and can be turned on or “latched” when the initiating current exceeds a threshold value that allows the feedback process to begin. Thus, when an energetic particle traverses the region of a CMOS integrated circuit containing the parasitic n-p-n and p-n-p transistors, it can generate enough current to trigger the thyristor, provided the particle has sufficient linear energy transfer. If this happens,

Single-event latch-up is triggered when a heavy ion causes current to flow unregulated between components on an integrated circuit. When PMOS and NMOS transistors are integrated into

the effected portion of the CMOS integrated circuit will be driven into latchup.

As long as the power supply maintains the voltage equal to or greater than the thyristor “holding” voltage, the latchup condition remains. The entire integrated circuit must be powered down to correct the condition. In many cases, the current is sufficient to burn out the transistors or metallization in the latchup path, permanently damaging the circuit (a phenomenon known as single-event burnout). In other cases, latchup does not cause damage, and the device is universally recoverable. The outcome depends on the circuit design, the geometry, and the presence of any current-limiting resistances. This serious problem makes it very difficult to use most commercial integrated circuits in an environment where heavy-particle radiation may be encountered. Bipolar integrated circuits are particularly sensitive to latchup.

Other single-event phenomena are even more complex. For example, in certain MOS transistors, the gate oxide can be ruptured by the passage of a cosmic ray. While not completely understood, this so-called single-event gate rupture may be caused by a combination of charge-multiplicative breakdown and injection of charges into the gate oxide.

### Conclusion

Understanding how space radiation interacts with microelectronics is the first step in establishing ways to mitigate adverse effects. Research at Aerospace has been instrumental in revealing the underlying mechanisms that lead to radiation-induced effects. Semiconductor manufacturing processes continue to evolve, and new technologies present new opportunities for complex interactions. Continued research at Aerospace will help spacecraft designers and mission planners account for all possible failure modes.

### Further Reading

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T. P. Ma and P. V. Dressendorfer, *Ionizing Radiation Effects in MOS Devices and Circuits* (Wiley-Interscience, New York, 1989).

G. C. Messenger and M. S. Ash, *The Effects of Radiation on Electronic Systems* (Van Nostrand Reinhold, New York, 1992).

G. C. Messenger and M. S. Ash, *Single Event Phenomena* (Kluwer Academic Publishers, New York, 1997).

Material	Density $\rho$ (g/cm <sup>3</sup> )	Ionization energy $E$ (eV)	Generation rate $g = 6.25 \times 10^{15} \rho/E$ (no. electron-hole pairs/gray-cm <sup>3</sup> )	P-n junction induced current for 1000 gray/s $I_p$ $\mu\text{A}/\text{cm}^3$
Silicon	2.328	3.6	$4.0 \times 10^{15}$	6.41
Gallium arsenide	5.32	4.8	$7.0 \times 10^{15}$	11.2
Germanium	5.33	2.8	$1.2 \times 10^{16}$	19.2
Silicon dioxide	2.27	18	$8.2 \times 10^{15}$	—
Air	$1.205 \times 10^{-3}$	34	$2.2 \times 10^{11}$	—

This table shows how to obtain the number of electron-hole pairs generated per unit volume per unit radiation dose for three different semiconductors (as well as for oxide and air for comparison). In the last column, this generation rate has been converted to the induced current per unit of semiconductor volume (in cubic microns) for a fixed dose rate of 1000 gray per second. For other dose rates, the induced current scales linearly.

# Picosecond Lasers for Single-Event Effects Testing

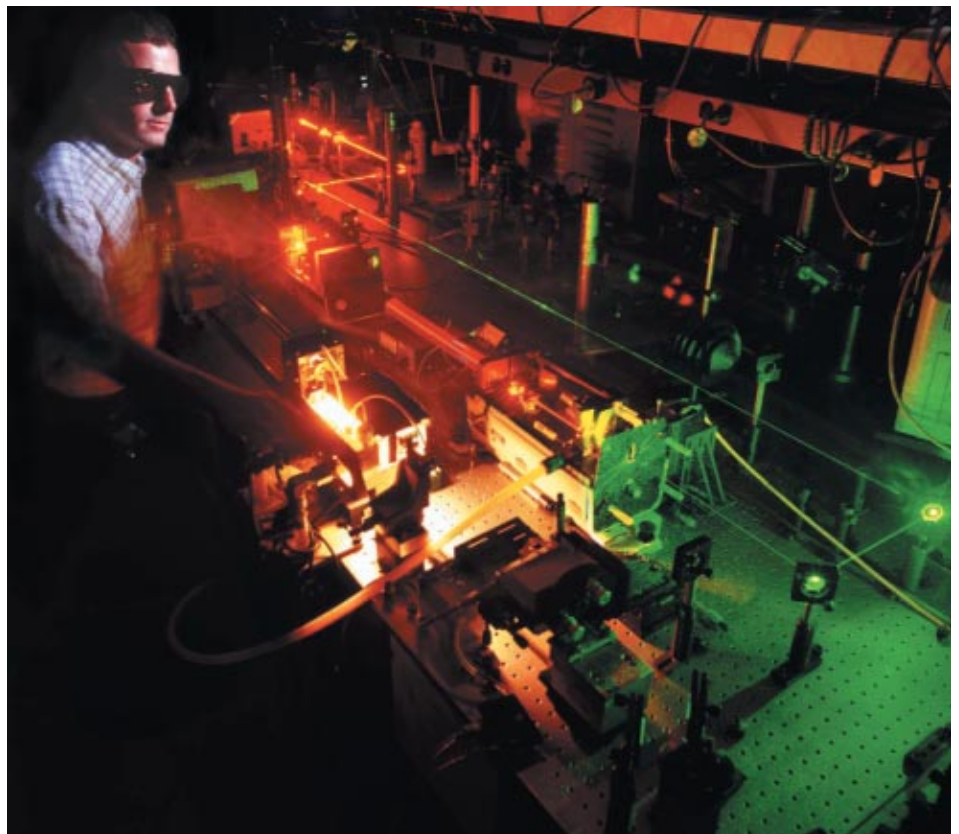
*In the past 10 years, Aerospace has developed a state-of-the-art facility that uses picosecond laser pulses to simulate the transient effects of energetic particles striking microelectronic devices. This system is used to diagnose radiation-hardened designs and to validate radiation-hardening techniques for mitigating the effects of space radiation on integrated circuits.*

**Steven Moss and  
Stephen LaLumondiere**

**M**icroelectronic and optoelectronic devices used in satellite systems must operate in an extremely harsh environment. Energetic particles can strike sensitive nodes in devices, causing permanent damage or transient events. Phenomena associated with the trail of charge produced by the strike of a single energetic particle are commonly referred to, by members of the radiation-effects community, as single-

event effects. These can cause temporary or permanent changes in the state or performance of a device.

Testing microelectronics for their susceptibility to single-event effects is typically done by exposing them to an ion beam from a particle accelerator. This method simulates the hostile space environment fairly well, but can be both costly and time consuming. To meet the need for a cheaper alternative, Aerospace began



The interaction of a picosecond laser pulse with a semiconductor material can generate a high density of electron-hole pairs (also known as charge carriers), much like the passage of an ionizing particle through the device.

investigating the feasibility of using laser pulses to simulate the effects of energetic particles in 1992.

Thanks to intensive efforts in the laser-test community, laser-based testing of microelectronic devices for single-event effects has gained widespread acceptance in the radiation-effects community as a useful complement to traditional testing methods. Today, the driving force behind the use of this technique is the ability to pinpoint sensitive nodes with submicron accuracy.

### Laser Simulation of Cosmic Ray Effects

The interaction of a cosmic ray in an integrated circuit generates a dense electron-hole plasma inside the semiconductor material; so does the absorption of a picosecond laser pulse. Both the particle and laser interactions occur on a short time scale—much shorter than the response time of most microelectronic devices. Although the initial charge profile produced by absorption of a laser pulse is somewhat different from that produced by the interaction of a cosmic ray, both events produce a highly localized trail of charge capable of generating single-event effects in microelectronic devices.

Testing with heavy ions consists of irradiating the entire device in a particle-beam accelerator and determining the upset-sensitive cross section based upon the incident ion flux and the number of upsets observed. The technique is global in nature, generally indicating whether or not an upset occurred, but not where on the device it originated. Also, because the technique relies on random particle strikes over the entire area of the device, temporal information is lost.

Testing with a pulsed laser provides several capabilities not offered by particle-beam testing. For example, the small spot sizes achievable with a laser and the ability to precisely position the device relative to the laser beam allow sensitive device nodes to be pinpointed with submicron accuracy. The laser produces no permanent damage in the device, so repeated measurements

can be made at a single sensitive location. The laser pulse can also be synchronized with the clock signal of the device to study temporal effects on sensitivity to single-event phenomena.

The laser system can also be used to verify operation of test equipment before embarking on the more costly journey to an accelerator facility. Unlike most particle-beam facilities, the laser facility does not require devices to be placed in a vacuum chamber for testing, and support electronics can be located close to the device under test. This is an extremely important feature when testing high-speed devices for their susceptibility to single-event transients.

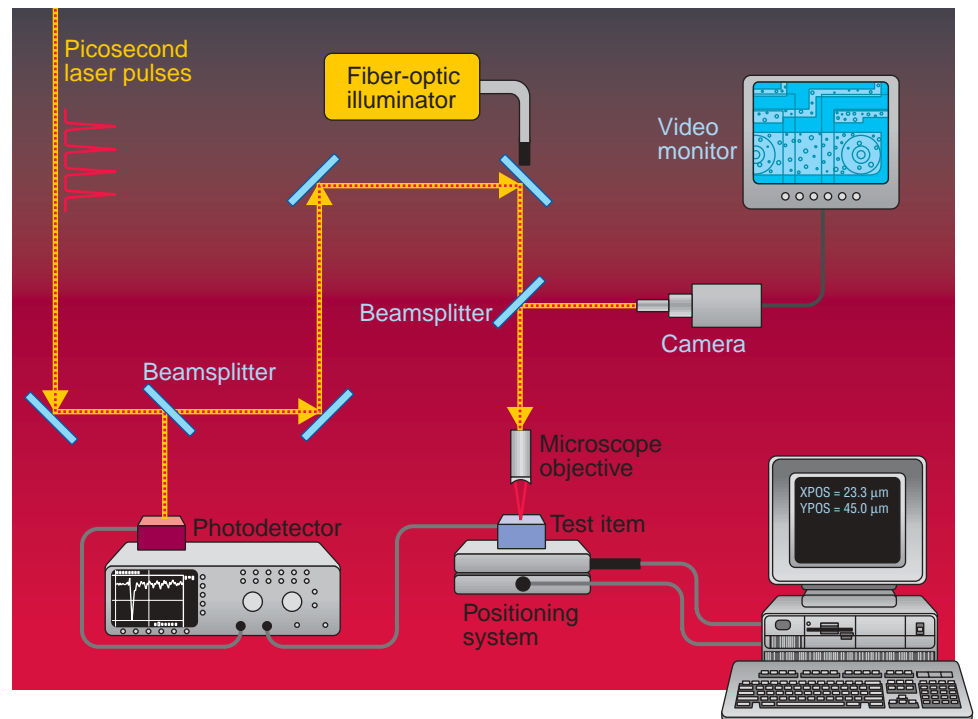
The practicality of this technique is limited by the inability of the laser light to penetrate metal layers covering sensitive device nodes. Complex devices with many

layers of metal limit the ability to determine the amount of incident light on a sensitive junction; however, other approaches such as thinning and testing devices from behind are viable alternates to the standard front test method.

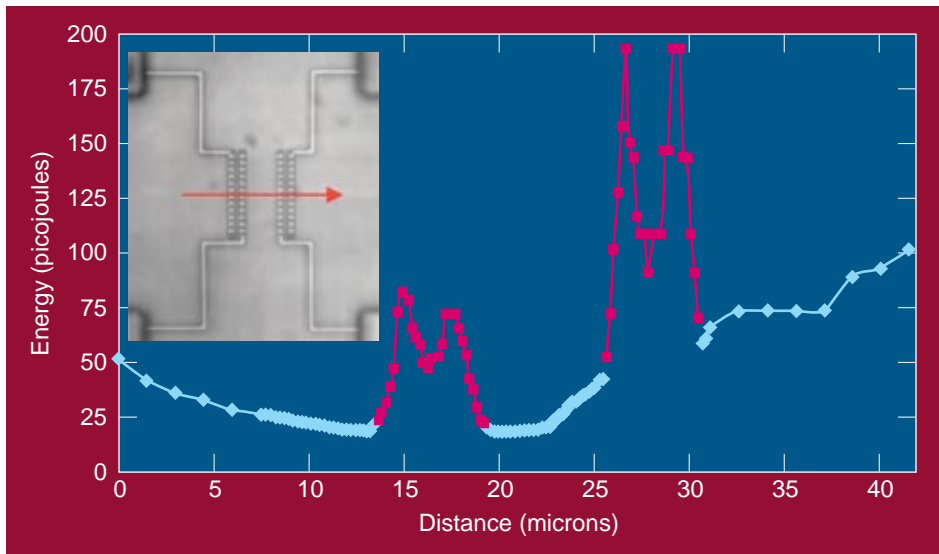
### The Facility

Over the years, various organizations in the United States have used lasers to simulate single-event effects, but only Aerospace and the Naval Research Laboratory currently possess dedicated laser facilities for this work. Researchers in the radiation-effects community have come to rely upon these facilities because of the unique capabilities they provide.

For example, the Aerospace laser test system can produce a train of pulses at a variable repetition frequency or operate in a single-shot mode. The system uses dye



In testing for susceptibility to single-event effects, a technique known as mode-locking is used to generate a train of laser pulses, each of which lasts only a few picoseconds. An electro-optic shutter grabs individual pulses, which are then focused through a microscope onto the device under test. A camera attached to the microscope shows the position of the laser beam. Devices are scanned beneath the laser beam to locate sensitive nodes. High-speed digital oscilloscopes, transient digitizers, and logic analyzers capture the response of devices to charges generated in the semiconductor material by the incident laser pulse.



A detailed one-dimensional sensitivity map displaying the threshold laser pulse energy required to induce latchup in the four-terminal test structure. The inset shows the location and direction of the scan. The most sensitive location (i.e., the location requiring the least pulse energy for latchup) is found near the edge of the negative-current well. The two double peaks represent where the laser was scanned over the metal contacts. The metal lines block any incident laser light. The laser spot has a Gaussian spatial profile with a spot size on the same order as the width of the metal lines. Consequently, there is always some light that propagates past the metal lines into the device, even when the laser spot is centered on one of the lines. Thus, the devices can still be latched up by increasing the laser pulse energy; however, as shown here, this requires a considerable increase in energy.

lasers to generate picosecond optical pulses; the laser wavelength can be tuned over the visible spectrum and into the near infrared.

Two wavelengths are generally used at Aerospace to measure laser-induced single-event effects. The first, 600 nanometers, has a penetration depth of about 2 microns in silicon. The second, 815 nanometers, has a penetration depth of about 12

microns. The ability to vary the penetration depth allows for detailed studies of charge-collection mechanisms in a variety of devices. The ability to control the range—and the energy deposited over that range—is not easily achievable in accelerator-based testing. The penetration depth of an energetic particle depends on both the particle energy and its mass. In order to test at two

## Origins of Laser Testing for Single-Event Effects

The first published report of using a pulsed laser to simulate the effects of ionizing radiation on microelectronic devices dates back to 1965. In that study, nanosecond pulses ( $10^{-9}$  seconds) from a Q-switched Nd:YAG laser were used to simulate dose-rate effects (the type of effect that would be encountered from a nuclear detonation) on integrated circuits.

Although the potential for focusing a laser beam onto individual transistors in more complex devices was also realized at this time, no one thought about applying this technique to the study of cosmic-ray-induced single-event effects because no one had yet witnessed single-event effects in microelectronic devices.

In fact, the first confirmed on-orbit upsets from heavy ions were not reported until 1975. These upsets were attributed to galactic cosmic rays triggering J-K flip-flops on a communications satellite (a J-K flip-flop is a basic two-state memory component).

A limited amount of work was performed in this area in the late 1970s and early 1980s; however, by the mid-1980s, researchers from a number of different laboratories had opened the investigation into the potential of picosecond laser pulses for simulating cosmic-ray-induced single-event effects in microelectronic devices. By the latter part of the 1980s, picosecond laser pulses were being used to simulate transient radiation effects at the Naval Weapons Center, Naval Research Laboratory, Jet Propulsion Laboratory, and at various defense contractors and laboratories around the world.

different ranges with particles of the same linear energy transfer, particles with different mass are typically required (linear energy transfer is the amount of energy deposited per unit length by a particle along its path through a material). The Aerospace team that uses the Lawrence Berkeley cyclotron performs tests using a variety of particles with different energies and different masses, which allows characterization of most devices over a wide range of linear energy transfer (see “Heavy-Ion Testing for Single-Event Effects”).

In the Aerospace laser test facility, the device test fixture is mounted on a computer-controlled, two-dimensional positioning system and raster scanned beneath the laser beam. Positional accuracy is 0.1 micron. The laser beam is focused onto the device with a custom-built microscope. A camera attached to the microscope allows investigators to observe the exact location of the laser beam on the device. Various microscope objectives provide useful magnifications between 100× and 1000×, and the spot size of the incident laser beam can be varied between approximately 1 and 150 microns.

The testing process generally begins by scanning a device with the large-diameter laser spot at low magnification to identify sensitive regions. During this initial scan, both spatial coordinates and images of the sensitive regions are recorded.

Once the large-spot scan has been completed, a tightly focused laser spot at higher magnification is used to pinpoint sensitive nodes within the regions identified during the large-spot scan. The threshold for single-event effects can be determined by reducing the incident pulse energy until single-event effects are no longer observed. A fraction of the optical signal is sampled by a photodiode and monitored on an oscilloscope for calibrating the laser-pulse energy incident on the device. Thorough calibration of the system includes measurements of the reflectance from the semiconductor surface at sensitive locations.

## Aerospace Activities

Early work at Aerospace focused on establishing a relationship between single-event effects induced by the pulsed laser and by energetic particles. For these measurements, basic four-terminal latchup test structures were chosen. These structures are routinely used for latchup research and are the simplest that can be used to study this phenomenon in complementary metal-oxide semiconductor (CMOS) devices.



Results from these measurements showed that it was possible to correlate the thresholds for heavy-ion-induced latchup and laser-induced latchup in CMOS devices from a number of different vendors. Additional studies were performed to validate the effectiveness of various techniques to produce devices that were “hardened by design” (see “Designing Integrated Circuits to Withstand Space Radiation”).

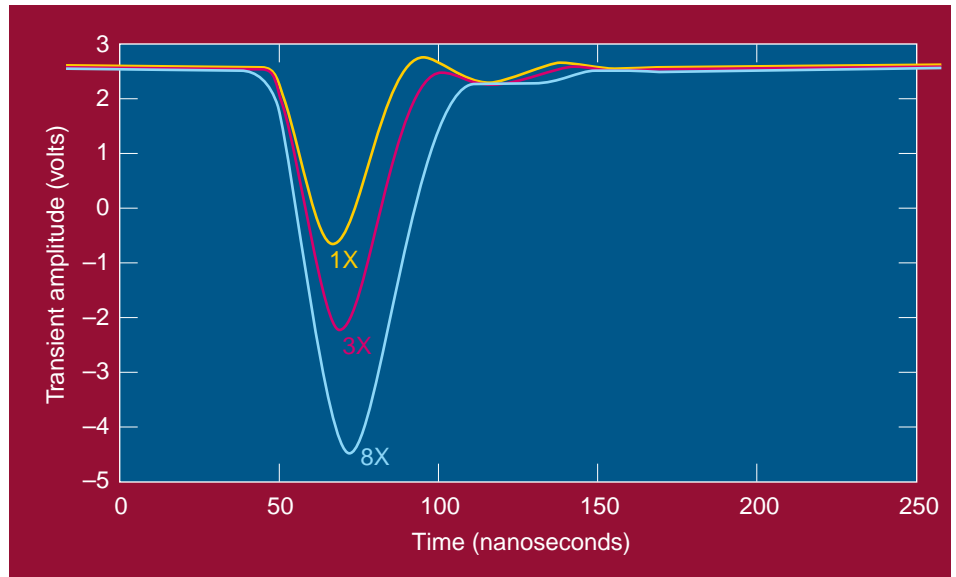
More recently, Aerospace has been investigating single-event upsets, single-event latchup, and single-event transients in various analog, digital, and mixed-signal devices.

### Transient Testing

Single-event transients appear as brief current spikes that can lead to anomalies in other components, such as logic circuits, downstream from the affected component. They can also propagate through logic gates in digital integrated circuits and be captured as upsets by clocked logic.

The commercial demand for high-speed, low-power devices is driving down the minimum feature sizes in microelectronics. As a result, single-event transients are causing greater concern for space-systems engineers. Reduced feature sizes and operating voltages mean that less charge is required to generate upsets, and also mean that modern devices will be fast enough to respond to single-event transients that were too short to propagate through older, slower logic.

Aerospace first reported the use of a picosecond laser as a diagnostic tool for understanding the origins of single-event transients in analog devices in 1993. Operational amplifiers, known to experience single-event transients on orbit, were first tested with heavy ions at a cyclotron and then subjected to laser testing to identify



Single-event transients from linear integrated circuits can be captured and registered as logical upsets in digital integrated circuits. The amplitude and width of this transient disturbance is proportional to the amount of charge collected by the sensitive device node. The use of picosecond lasers for this type of testing has aided in explaining the transient behavior of individual transistors in more complex integrated circuits. The three transients depicted here show how a single transistor in a high-speed operational amplifier responds to different amounts of energy deposited by the laser. The greater the amount of deposited energy, the larger the peak amplitude and width of the disturbance. For simplification, the energy deposited by the laser pulse has been normalized to the smallest amplitude transient.

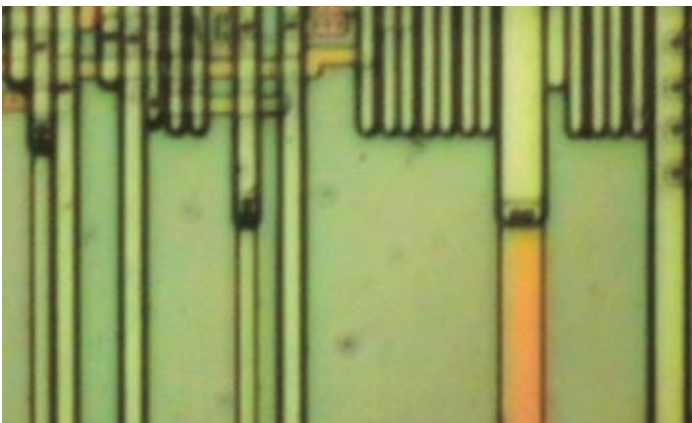
the approximate areas of sensitive transistors. The results showed that the laser could be used to identify sensitive transistors and to reproduce the transient behavior observed during energetic particle tests.

Since then, pulsed lasers have been used on numerous occasions to complement a limited set of particle-beam data and to expand the knowledge of how device sensitivity varies under different operating conditions. To date, laser-based testing has been used to examine single-event transients in a variety of analog devices commonly found in space systems, including operational amplifiers, comparators, and mixed-signal components.

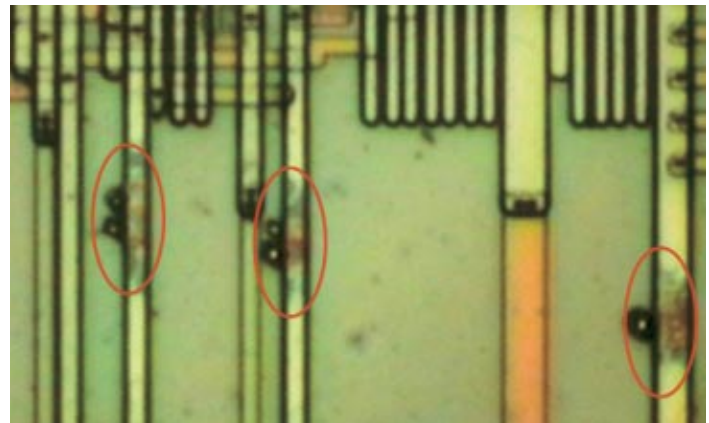
### Latchup Testing of Commercial Parts

Recently, Aerospace collaborated with researchers from NASA’s Jet Propulsion Laboratory (JPL) to identify the mechanisms responsible for destructive failures observed in an analog-to-digital converter induced by heavy ions during latchup testing. A substantial number of these devices suffered catastrophic failures during these tests, but the complexity of the devices made it difficult to identify the failure mode.

By using the pulsed laser, Aerospace was able to pinpoint the sensitive nodes and view, in real time, the destructive failure mode. This allowed the researchers from



Before and after images showing destructive failure of metal lines in an analog-to-digital converter as a result of latchup. The highlighted regions



(in the photo on the right) are areas where molten metal was ejected from the metal line.

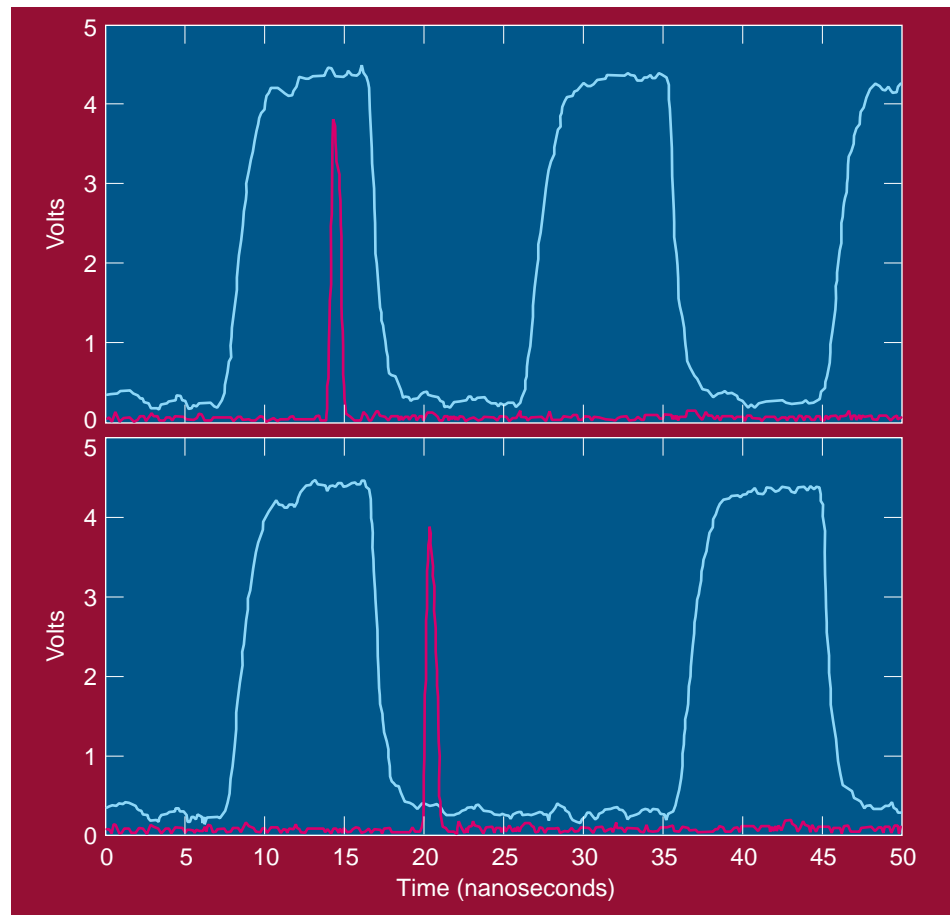
JPL to determine that the current density from latchup was so great in these converters that the aluminum metal lines were actually melting and ejecting molten aluminum from beneath the metal encapsulant layer.

Once the location of this failure mechanism had been identified with the pulsed laser, the devices were reexamined using heavy-ion irradiation, and the same failure mode was obvious. The laser tests also provided direct evidence for nondestructive, latent damage to metal lines and vias subject to such high-current densities as a result of latchup. These were the first experiments in which destructive failures and latent damage were observed and recorded in real time.

Aerospace has also tested a number of complex microprocessors and digital signal processors. In the case of the Motorola 68302 microprocessor, for example, heavy-ion testing revealed a number of different single-event upset signatures and indicated that the device was fairly sensitive to energetic-particle-induced latchup; however, observations had not shown this microprocessor to be prone to latchup on orbit. The laser was used to probe the different parts of the microprocessor responsible for these types of effects and pinpoint the nodes that were sensitive to latchup.

Agreement between the laser-based test and the heavy-ion test led investigators to look for an alternative explanation for the apparent absence of latchup events on orbit. They noted that the telemetry data from the satellite allows checking of the device current only 0.0002 percent of the time. They therefore concluded that the part probably is experiencing latchup on-orbit, but the high-current state is not detectable because the limited duty factor of the sampling telemetry makes it highly unlikely that a high-current event will be detected before the system is reset (effectively correcting the latchup condition).

In another instance, Aerospace assessed the single-event latchup vulnerability of a 24-bit digital signal processor for the Mil-satcom program office. A highly detailed map of latchup-sensitive locations on this device was generated, and more than 3700 individual nodes were identified as being susceptible to laser-induced latchup. Some of these sites were susceptible at low linear energy transfer values, which indicated that the part would probably experience latchup on orbit. As a result, researchers concluded that this part would



By synchronizing the clock frequency of a device with the laser pulse, the temporal dependence of single-event upset on clock cycle can be investigated using a pulsed laser. The upper traces in this figure show the laser pulse arriving just prior to the falling edge of the clock signal and no upset observed at the device output; however, whenever the laser pulse arrives slightly after the falling edge of the clock waveform, the next clock cycle is phase shifted, or delayed in time by one-half of the clock period.

not be an acceptable candidate for the mission under consideration.

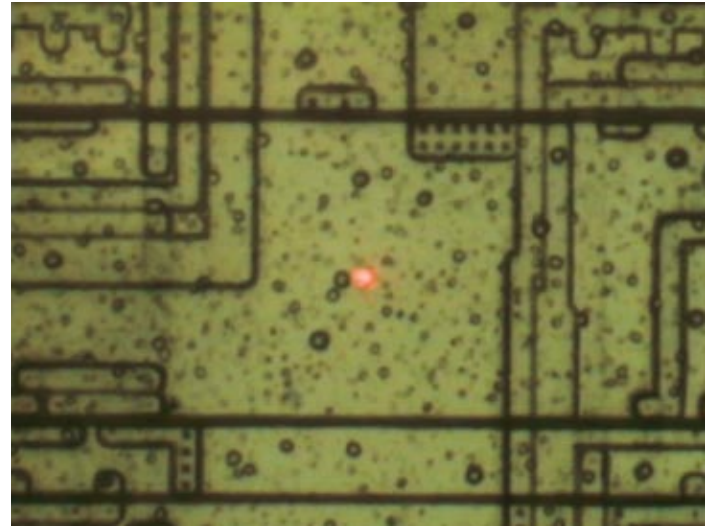
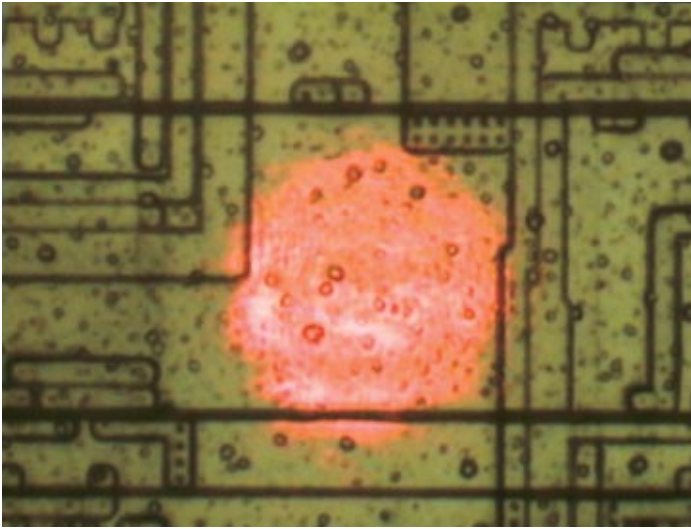
### Validating Hardened Designs

Heavy-ion tests on memory cells designed to be resistant to single-event effects generated both single-event upset and single-event latchup. In accelerator-based testing, little information could be extracted from these tests because the latchup threshold was only slightly higher than the upset threshold. Irradiation of the entire device produced latchup and upsets randomly; however, in many instances, the device experienced upset but was then driven into latchup before information about the upset could be retrieved. Consequently, for devices such as these, it was not possible to cleanly extract information about the upset threshold and cross section using the standard, heavy-ion test procedures.

Because the laser beam can be focused onto a single node, Aerospace used the pulsed laser to identify the locations responsible for latchup and then conducted a detailed analysis of the device layout to

identify the root cause. Laser testing was also used to identify the nodes responsible for the upset, without any interference from the latchup problem. Electrical simulations of the circuit then helped reveal an unexpected dual-node upset mechanism. The upset was a result of simultaneous charge collection at two sensitive locations. Understanding the mechanisms responsible for the high sensitivity to single-event effects allowed for circuit design changes that improved the memory cells' resistance to single-event effects.

Similarly, heavy-ion single-event testing of an application-specific integrated circuit identified a susceptibility both to single-event latchup and single-event upset. The linear energy transfer threshold for inducing latchup was low enough to prompt the use of the pulsed laser to identify areas on the chip that were responsible for these events. The results from these measurements were provided to the contractor, and the circuit was redesigned with appropriate modifications. Subsequent testing showed no evidence of latchup.



The use of a large-diameter laser beam allows for rapid identification of regions in complex integrated circuits that are susceptible to single-event effects. A tightly focused laser beam, on the order of a micron in diameter, can then be used to precisely pinpoint sensitive junctions at the transistor

level. This technique provides valuable information to the designer who is interested in understanding and mitigating single-event effects in spaceborne microelectronics.

A radiation-hardened version of a 32-bit digital signal processor was also tested for laser-induced latchup and compared with the corresponding commercial version. During heavy-ion testing, the hardened devices exhibited no latchup for effective linear energy transfer values as high as 120 MeV-cm<sup>2</sup>/mg.

The commercial version, on the other hand, exhibited latchup during heavy-ion testing at an effective linear energy transfer value of only 12 MeV-cm<sup>2</sup>/mg. In fact, laser testing allowed the identification of more than 60 single-event latchup locations on this device. The same locations on the hardened version were then interrogated with the laser, but no latchup was observed. This result provided confidence in the radiation-hardened design and further confirmed the effectiveness of the laser for latchup screening of hardened devices.

### Continuing Investigations

Aerospace is involved in collaborative research efforts to study novel approaches for hardening commercially available integrated circuits against single-event latchup. Additional efforts seek to gauge the space suitability of commercially available devices that take advantage of advanced manufacturing processes. The picosecond-laser facility is also being used to study the effectiveness of various design strategies for mitigating the effects of single-event transients in digital integrated circuits.

High-speed integrated circuits are transitioning from silicon-based semiconductors

to compound semiconductors, such as gallium arsenide, indium phosphide, and silicon germanium. Aerospace investigation of these devices will include the picosecond laser system to help characterize their sensitivity to single-event effects.

While laser-induced single-event effect testing will not replace conventional particle-beam testing, it has become a well-established technique for providing a better understanding of the nature of single-event effects in complex modern microelectronic devices and for validating design-hardening methods to mitigate single-event effects in these devices.

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# Heavy-Ion Testing for Single-Event Effects

*The most reliable way to reproduce the space-particle environment on Earth is with a particle accelerator such as a cyclotron. Aerospace has conducted numerous tests measuring the susceptibility of microelectronic devices to single-event effects.*

Susan Crain and  
Rocky Koga

The liftoff of the Atlas Centaur launch vehicle seemed picture-perfect: The rocket completed its ascent and successfully deployed its payload to its intended orbit. What was not immediately apparent was that some bits in the computer memory were altered as the vehicle flew through a region of space dense with energetic protons. In this case, the errors were automatically detected and corrected by the computer—but could the launch team always count on such good fortune?

Events such as this have led to the realization that spaceborne microcircuits are vulnerable to galactic cosmic rays and trapped protons. Since the discovery of so-called “single-event upsets” in 1975, scientists have sought to characterize the space-radiation environment in greater detail and understand its interactions with microelectronics.

Ideally, the study of space-radiation effects should be conducted in a manner that approximates, as closely as possible, the space-radiation environment. The most reliable test would use all of the same ion types that are found in space and allow measurement over a wide energy range for each. But such a test would be prohibitively expensive. A more practical approach is to use a medium-energy particle accelerator to simulate galactic cosmic rays and trapped protons in space-radiation environments.

The ability of an ionized particle to interact with materials is a function of its linear energy transfer (LET) value. LET is essentially the measure of ionizing energy deposited in a material per distance traveled, generally rendered in millions of electron volts per square centimeter per milligram (MeV-cm<sup>2</sup>/mg). For particles in space, the range of LET varies primarily

from a few hundredths to just under 100 MeV-cm<sup>2</sup>/mg. Particles with low LET values are far more abundant than particles with high LET. Thus, in investigating a particular device, researchers seek to find the threshold value and to determine the magnitude of sensitivity at large LET values. Such an investigation requires an accelerator capable of generating many particles with different LET values.

## The Facility

The choice of accelerator is based on its capability to produce ions with a reasonable particle range for a wide range of LET values. Other factors include the ease of use and cost of operation. Aerospace has traditionally used the 88-inch cyclotron at Lawrence Berkeley National Laboratory.

This cyclotron routinely and reliably accelerates ion species as light as protons and as heavy as gold. To achieve high energy without losing high intensity, it employs a sector-focused design. A process known as electron cyclotron resonance is used to generate the ion source; the ions are then injected into the cyclotron for acceleration. This technique allows continuous operation of the cyclotron for up to several weeks. Also important, it allows researchers to modify the ion intensity with the push of a button.

The Berkeley cyclotron can produce several ion species of various LET values. A typical test run might use a half dozen different ion types ranging in mass from boron to xenon, each capable of penetrating to different depths within the target device. The ions can be switched in a matter of seconds, making single-event effects testing highly efficient.

The beam diameter is about 7.6 centimeters, within which the target position is determined by a laser targeting system. The beam may be directed to a small section of

Test boards often accommodate several devices for testing, eliminating the need to vent the chamber to change the parts. The control software for the motion system logs the unique spatial information for each part so it is always centered in the beam line even when it is angled to achieve effective LETs.

a microcircuit or to a large detector. The ion flux range is between a few particles to a few hundred thousand particles per square centimeter per second. A low flux is used for sensitive devices, and a high flux is used to check for rare events. A surface-barrier detector for energy measurement and a position-sensitive detector serve to identify ion species, energy, and uniformity. A diagnostic/dosimetry apparatus verifies that the beam is suitable for the type of testing being performed.

The irradiation chamber measures 96.5 × 99 × 116.8 centimeters. Vacuum is controlled by a high-capacity system of pumps capable of evacuating the chamber in about four minutes. This makes sample changes quick and easy. A mechanized, remote-controlled system moves individual test samples in and out of the beam and changes beam-exposure angles. Changing the beam-exposure angle effectively changes the charge deposition in the sensitive region of a microcircuit. Charge deposition is related to the concept of “effective LET,” which is calculated by multiplying the LET of the incident ion by the secant of the angle between the incident beam and the chip-surface normal.

### Test Methodology

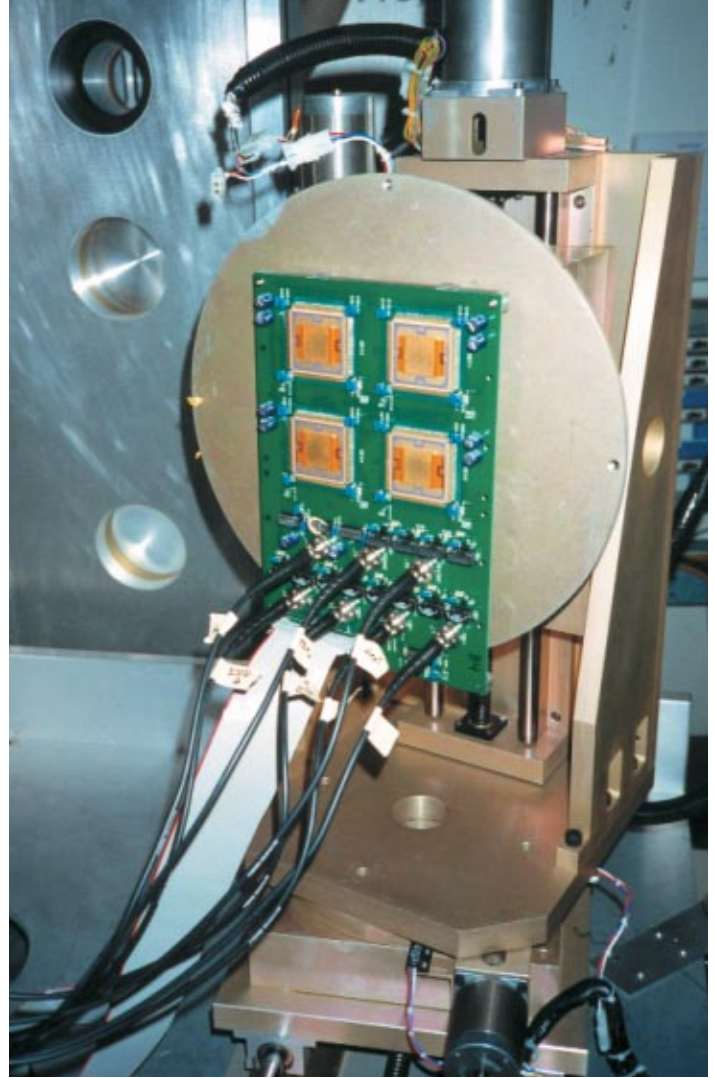
The facility at Lawrence Berkeley National Laboratory has been used to test all kinds of devices and circuits. In the past, some electronics manufacturers maintained separate production lines for radiation-hardened devices, and the cyclotron was used to examine these parts. With the subsequent increase in commercial space systems, designers sought to use cheaper off-the-shelf devices, and the cyclotron was used to assess their potential for particular missions. More recently, the cyclotron has been used to evaluate a technique known as “radiation hardening by design,” which uses specific design principles to increase the radiation resistance of components produced via standard commercial foundries.

The Aerospace single-event effects testing program has investigated both military and commercial products. Often, a commercial device will be tested to determine

whether it can pass as a rad-hard product according to military specifications. Other testing efforts involve the characterization of board-level circuits for space systems using commercially available parts.

Ground testing of devices for use in military, commercial, and research efforts is done using specially designed testers. The process involves exposing a part to a particle beam while monitoring its function. By counting the number of upsets and knowing how many particles passed through the part, investigators can calculate the likelihood that a particle strike will cause a single-event effect. Such calculations may be used to produce a set of sensitivity curves for a microcircuit type, which can in turn be used to estimate the upset rate of the microcircuits for various orbits.

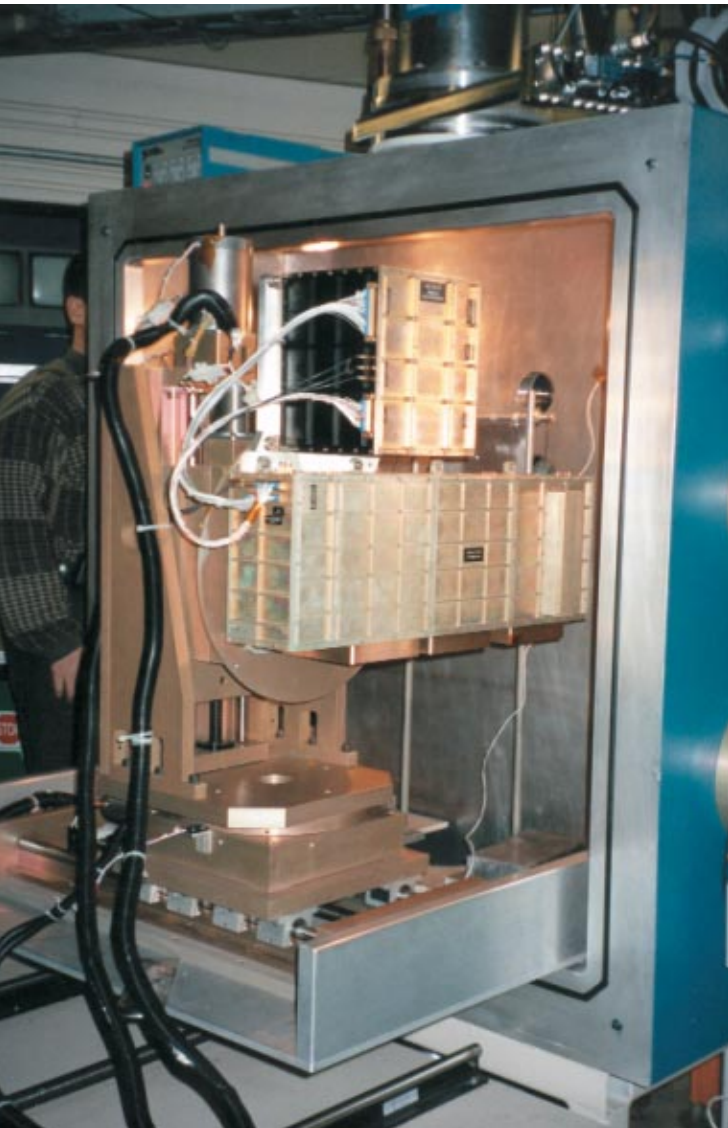
A microcircuit may respond differently depending on factors such as case temperature, clock speed, and cumulative total dose. In addition, the vulnerability for one microcircuit type to different types of single-event effects varies at different energy values for heavy ions and protons. These are some of the many parameters that must be carefully monitored.



In general, a device is first tested for destructive single-event effects such as latchup, burnout, and gate rupture. If the device does not display latchup, for example, or if the onset of latchup is at a high enough LET value to be tolerable for the particular mission, then the device will be tested for nondestructive effects.

Ion	Energy (MeV)	LET (MeV-cm <sup>2</sup> /mg)	Range in silicon (microns)
<sup>11</sup> B <sup>+3</sup>	108.2	0.89	323
<sup>18</sup> O <sup>+5</sup>	183.5	2.19	228
<sup>22</sup> Ne <sup>+6</sup>	216.3	3.44	179
<sup>40</sup> Ar <sup>+11</sup>	400	9.88	129
<sup>51</sup> V <sup>+14</sup>	508.3	14.8	116
<sup>65</sup> Cu <sup>+18</sup>	659.2	21.6	108
<sup>73</sup> Ge <sup>+20</sup>	724.7	25.37	104
<sup>86</sup> Kr <sup>+24</sup>	886	30.0	111
<sup>98</sup> Mo <sup>+27</sup>	983.6	38	102
<sup>136</sup> Xe <sup>+37</sup>	1330	53.7	104
<sup>136</sup> Xe <sup>+38</sup>	1403.4	53.6	110

Ten-MeV-per-nucleon particles are used more frequently with parts that cannot be easily delidded. Often, parts such as DRAMs need to be lapped from the back side of the die to avoid the lead frame, so the beam needs to have a greater range to pass through the sensitive regions. Berkeley is developing still more penetrating cocktails of ions.



The chamber is designed to accommodate large systems as well as single boards. This instrument is using the monoenergetic particle beams to calibrate its detectors before flight.

When assessing risk, the designer or program manager needs to consider the single-event effect data in the context of the circuit features and the intended mission. For instance, single-event latchup can be mitigated (rendered nondestructive) by watchdog circuits that cycle power when a current limit is reached; thus, a somewhat sensitive device might be considered suitable for a given mission provided that such watchdog circuits are included. However, because microelectronics are getting more complex, with denser and larger designs, such circuits might not be feasible. Some complex device architectures divide the circuits into sections powered independently using different supply voltages. In such cases, setting an appropriate current limit becomes a challenge, and may prohibit the use of a device in a particular orbit.

For nondestructive effects in a complex microcircuit, fully characterizing a device type takes about 12 to 16 hours of beam time. If the part is vulnerable to destructive effects such as gate rupture and burnout, the testing can take even longer. In more complex devices, single-event upset sensitivity in different areas of the circuit may vary, and the effects might have different onsets with respect to effective LET. Fortunately, the single-event upset will usually have a different signature for the different circuit elements. Separation of the effects can happen, but the time it takes to characterize the device increases.

### Testing Innovations

Through the years, Aerospace has developed specialized testers for characterizing a wide variety of devices. The most recent is the Aerospace Single Event Tester (ASSET), which provides a general-purpose interface for evaluating the single-event effect susceptibility of a wide variety of complex microcircuits. It employs

two general test methods—the memory test and the sequence test.

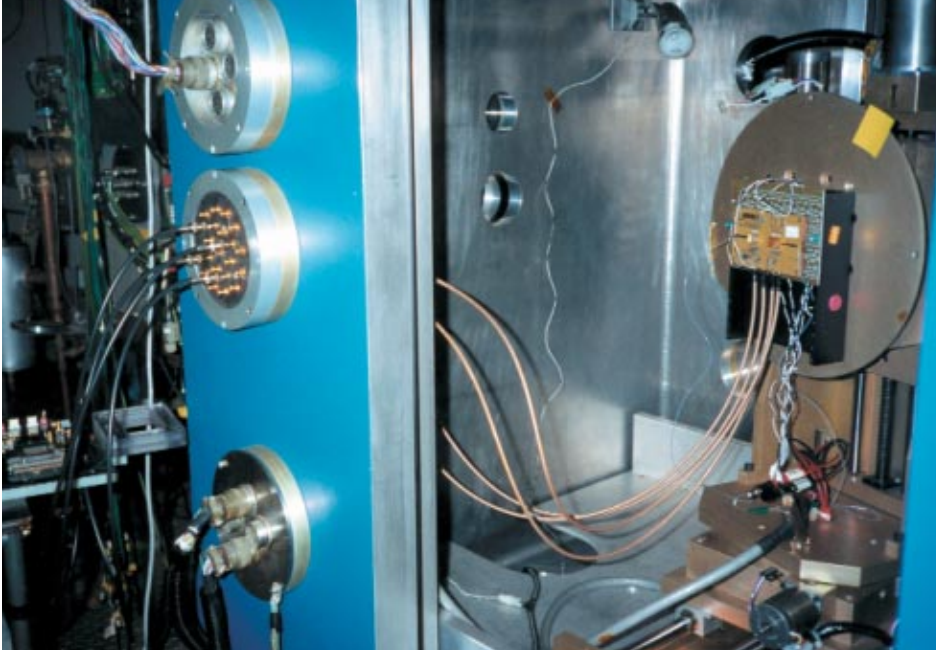
In memory-test mode, the system treats the device-under-test like a typical memory with some control lines, address lines, and data lines. The tester writes a known pattern to an array of addresses while the device is not being irradiated, and then reads it back to ensure successful writing. Then, while the device is exposed to the particle beam, the tester continuously reads the memory locations and compares them to what was written. Any discrepancy in a bit location is counted as an error. The tester communicates the error, the address location, and the cycle count to the host computer. Later, this stored information is analyzed for single-bit upsets, addressing errors, multiple-bit upsets, and stuck-bit errors. The error is corrected in the device,

and the test continues. The flux of the beam is kept low enough to keep the error-handling process manageable.

The sequence-test mode is used for a broader type of test. In this case, a sequence of patterns is stored temporally while the device is undergoing a normal function, without irradiation. This recorded pattern is then compared with the device outputs during exposure to the particle beam. This is the mode used to test more complicated microelectronics such as microprocessors, digital signal processors, and field-programmable gate arrays. In this way, the device can be running specialized programs designed to exercise particular sections such as the arithmetic logic unit or the cache, or application-specific programs. The tester can monitor up to 512 signals at 7 megahertz and can analyze patterns up to 64,000 words deep. The test protocol is set in firmware on ASSET under control from a host computer interfaced via an in-house specialized parallel bus protocol.

Recently, dynamic random-access memories (DRAMs) have attracted the attention of space system designers because of their high storage capacity. These and other complex devices such as synchronous DRAMs, microprocessors, digital-signal processors, flash memories, and even analog-to-digital and digital-to-analog converters have control registers that can be upset by radiation. Error detection and correction schemes can help mitigate single-event upset in memories, but if the control circuits experience single-event upset, then the function of the device can be completely impaired. The designer using a DRAM for a space application has many choices about how to implement operational modes such as “idle” and “refresh.” The selected implementation can affect the device’s radiation sensitivity. Aerospace has used ASSET to evaluate such devices. For one program, Aerospace exhaustively tested synchronous DRAMs not just from a number of manufacturers for comparison, but also in many different configurations, identifying the most robust scheme for writing, reading, and refreshing. Based on this data, the customer was able to redesign the control circuit and successfully implement a high-capacity memory design.

ASSET can distribute four different power supplies to as many as 32 different devices at a time. The supplies are floating with respect to ground, allowing for



The motion system on which the microelectronics being studied are mounted allows the user easy access. The control software will position the parts normal to the beam at the start of a run. The beam enters the chamber through the lower hole at the back wall. The chamber has several ports with various connector types available on interchangeable flanges.

inverted (negative) voltages as required. ASSET can also power thermoelectric coolers or heaters and monitor temperature. A cold plate is available for cooling of the test devices such as emitter-coupled logic parts or high-power devices like power converters. The devices to be tested are built onto daughter cards with a standard interface to the test head. This allows

many different devices with varying power, control, and interface requirements to be tested with the same basic system. The entire apparatus was designed to fit inside a vacuum chamber with the devices under test, enhancing signal integrity by eliminating long cables.

Aerospace is updating ASSET to make it more portable. It will be about the size of

a tackle box and will be faster and better able to handle low-voltage devices. It has also been designed to accommodate even more varieties of DRAMs, flash memories, and other memory types.

### Future Trends

The first heavy-ion tests at Berkeley in 1979 immediately led to the discovery of single-event latchup. Aerospace investigators were the first to identify several other kinds of single-event phenomena in various types of microcircuits. They include single-event snapback, single-event transients, single-word multiple-bit upset, and stuck-bits effect.

Despite this knowledge, microcircuits occasionally experience anomalies in space—often because of a lack of preflight investigation of radiation effects. When this happens, Aerospace may be called in to assist the anomaly investigation. Such efforts are necessary postlaunch activities; however, the trend is to assess the sensitivity of microcircuits to single-event effects prior to deployment in space. Designers and program managers are increasingly aware that a systematic investigation of all microcircuits is essential to ensure mission success—and prevention of single-event effects through component testing at development stages is perhaps the most cost-effective approach. As the microcircuits in space systems grow ever more complex, ground-based heavy-ion testing of spaceborne microcircuits becomes all the more essential.

### Further Reading

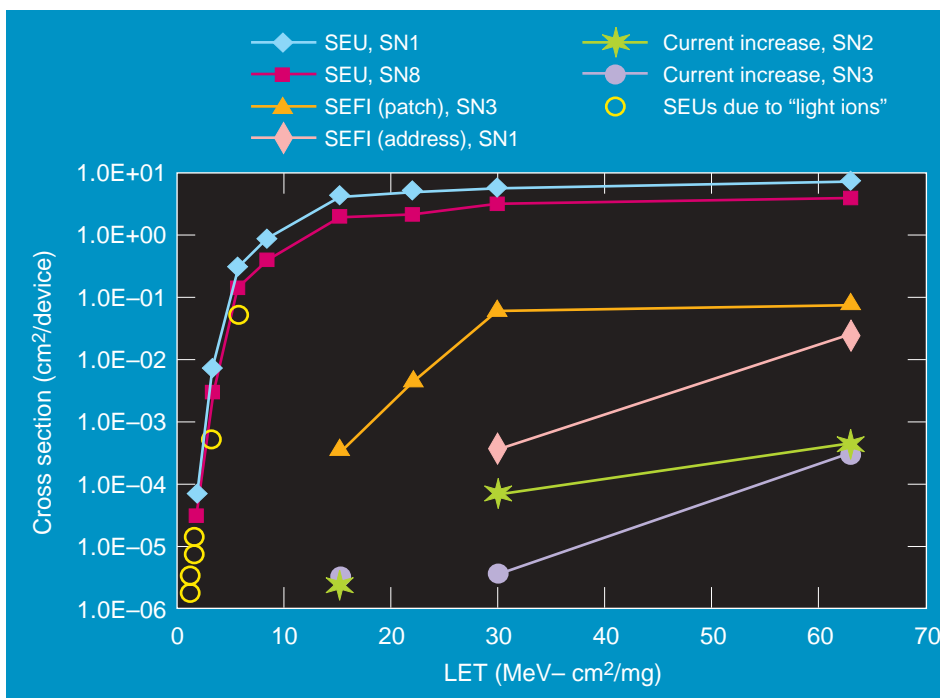
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This graph charts the sensitivity of a 256-megabit synchronous dynamic random-access memory (SDRAM) to heavy ions at 4.5 MeV per nucleon. The testing regimen looked for single-event upsets (SEU), single-event functional interrupts (SEFI), and stuck-bit effects. SEFI included errors to a patch in the memory, errors to consecutive address locations, and errors accompanying an increase in bias current.

# Designing Integrated Circuits to Withstand Space Radiation

*The high cost of maintaining dedicated foundries to create space electronics has motivated an exploration of alternatives for next-generation space systems. One approach in particular—the use of design techniques to mitigate the effects of space radiation on integrated circuits—is gaining wider acceptance.*

**Donald C. Mayer and  
Ronald C. Lacoë**

**T**he market for satellite components is small compared with the consumer microelectronics market, and manufacturers of integrated circuits have very little incentive to develop parts specifically for space applications. This presents a problem for satellite designers because space electronics must operate in an environment that is vastly different from what is seen on Earth. Space electronics are continually bombarded by energetic plasmas, particles, and other forms of radiation from the sun and galactic sources. This radiation can cause unpredictable spacecraft anomalies, and mission success can depend on how well the onboard electronics resist its effects. Components specifically designed to tolerate this environment are said to be “radiation hardened,” or simply “rad hard.”

During the past three decades, several companies have developed manufacturing processes to produce a range of rad-hard electronic products. These processes are somewhat different from the ones used in commercial foundries because they include a few modified process steps that produce circuits with greater radiation resistance. These parts are more expensive than their commercial counterparts and have lagged several generations behind in terms of processing speed, power, and size. Moreover, many companies that were in the business of supplying rad-hard components a decade ago have dropped out of the market. Only two remain active today.

Faced with rising costs and decreasing availability of space-qualified electronic parts, designers have been searching for

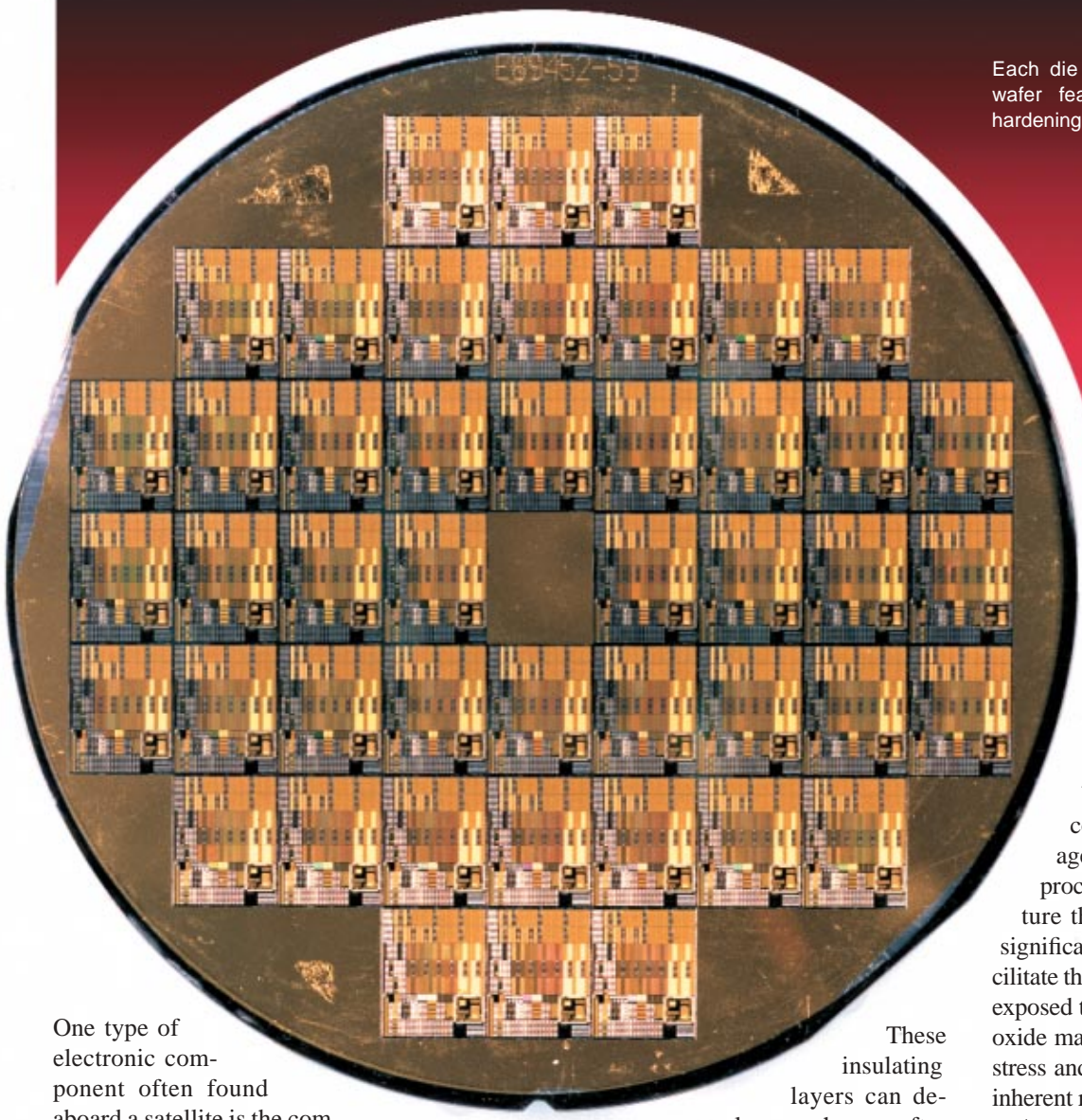
alternatives to the traditional dedicated rad-hard foundry approach. One strategy in particular has been gaining popularity in recent years. Known as radiation hardening by design (RHBD), this approach relies solely on circuit design techniques to mitigate the damage, functional upsets, and data loss caused by space radiation.

Aspects of this approach have been in use for some time, but most frequently in combination with dedicated rad-hard manufacturing facilities. More recently, a number of research institutions and corporations have demonstrated the basic feasibility of RHBD using standard commercial foundries; however, to satisfy the military’s need for a wide range of part types and hardness levels, a self-sustaining RHBD infrastructure must be established, and the RHBD approach must be proven robust enough to use without some degree of fabrication process control. Aerospace is working to develop this infrastructure while demonstrating the efficacy of design-hardening techniques.

## **Major Concerns**

Two types of space radiation are of particular concern for spacecraft electronics designers. The first, known as the total ionizing dose, represents the cumulative effect of many particles hitting a device throughout the course of its mission life, slowly degrading the device until it ultimately fails. The second involves high-energy particles that penetrate deep into materials and components, leaving a temporary trail of free charge carriers in their wake. If these particles hit vulnerable spots in the circuit, they can produce adverse effects, described generically as “single-event effects.”





Each die on this semiconductor wafer features early radiation-hardening-by-design techniques.

One type of electronic component often found aboard a satellite is the complementary metal-oxide semiconductor (CMOS) integrated circuit. CMOS devices use the simultaneous flow of both electron and hole currents through transistors and logic gates. (A “hole” is a quantum mechanical concept that is generally modeled as a “missing” electron in the semiconductor lattice.) The transistors that carry these negative and positive currents need to be isolated from each other; this is where space radiation can interfere.

#### Total Dose Effects

The manufacturing processes used to build commercial electronic components in the 1970s and 1980s were severely inadequate to meet the needs of the space community. But as commercial CMOS processes have advanced, the inherent radiation resistance of these devices has improved—and thus, the RHBD approach has become more feasible. For example, the current that flows through CMOS transistors is governed by a low-voltage gate over each device, isolated by a layer of oxide.

These insulating layers can develop a charge after long exposure to ionizing radiation, and this charge can affect the flow of current through the device; but as circuits have shrunk, the thicknesses of these insulating layers have decreased, presenting less opportunity for charge buildup.

More problematic are the radiation-induced increases in leakage current—unregulated current flowing across unintended areas of the semiconductor. When leakage current bypasses the transistor’s isolated regions, it degrades the distinguishability of the transistor’s “on” and “off” states. Leakage also increases the circuit’s background current, or the amount of current flowing when the device is in a quiescent state. Such an increase, multiplied by the tens of millions of switches in each circuit, can drive up power consumption, increasing heat-dissipation needs and prematurely draining the power source of the satellite. In an extreme case, the isolation between discrete components can also be lost, rendering the circuit useless.

The edges of the transistors where the thin gate oxide abuts the much thicker field oxide, which covers and insulates the border regions of the semiconductor, are also prone to leakage in a radiation environment. The process traditionally used to manufacture the transistor borders can induce significant material stress, which may facilitate the increase in leakage current when exposed to radiation. The newest isolation-oxide manufacturing processes impart less stress and seem to have achieved a greater inherent radiation resistance.

Aerospace has been testing the total-dose hardness of various commercially available CMOS manufacturing processes since 1995 by building test devices and irradiating them in a cobalt-60 radiation chamber. The latest results are encouraging. In some tests, several commercial CMOS devices withstood more than 100 kilorads of total-dose radiation, which is adequate for some space missions. Still, this level of inherent total-dose hardness may not be sufficient for many space applications. In these cases, additional immunity can be obtained using RHBD techniques.

For example, Aerospace and other companies have shown that total-dose effects can be mitigated by designing transistors in an enclosed shape, thereby eliminating the edges that can trigger current leakage along the borders of conventional transistors. Current flows from the center to the outside of these devices, making them immune to edge leakage current, but requiring a larger area for each transistor.

Furthermore, transistor-to-transistor leakage can be reduced by incorporating guard bands around individual transistors or groups of transistors. Other novel techniques are being applied to conventional transistor switches to boost their immunity to total ionizing dose radiation. These techniques consume area in the design, thereby reducing the total number of transistors available for a given circuit function and increasing the capacitance, and thus the power consumption, of the circuit. The trade-off may be worthwhile: Using RHBD, several researchers have demonstrated radiation hardness in excess of 20 megarads using commercial CMOS foundries, making them suitable for use in nuclear reactors as well as severe space environments.

### Single-Event Effects

While the hardness of CMOS circuits to total-dose effects has been improving, some single-event effects are becoming more problematic. Single-event effects occur when energetic particles penetrate the semiconductor, creating temporary “wires” of charge that produce spurious currents at critical circuit locations. When these particles strike sensitive nodes in the circuit, various adverse effects can occur, ranging from data upset to latchup or burnout.

RHBD techniques have shown some efficacy in mitigating particle-induced effects. For example, single-event latchup can occur when adjacent negative-current and positive-current transistors become shorted together through the current induced by an energetic particle. Aerospace tests indicate that this effect can be easily prevented using guard bands around adjacent devices. These guard bands, consisting of doped “trenches” in the silicon, greatly increase the current needed to trigger and sustain latchup, making these types of events much less likely in space.

Single-event upsets require different mitigation techniques. Single-event upsets occur when energetic particles deposit charge into memory circuits, causing stored data to change state (from a “1” to a “0,” for example). As circuits shrink and transistor volumes become smaller, the total charge needed to cause an upset in a circuit element decreases. Thus, even protons moving through the circuit may deposit sufficient charge to disrupt sensitive locations. Susceptibility to single-event upsets can be reduced by increasing the amount of charge needed to trigger a bit flip or by providing feedback resistors that give the

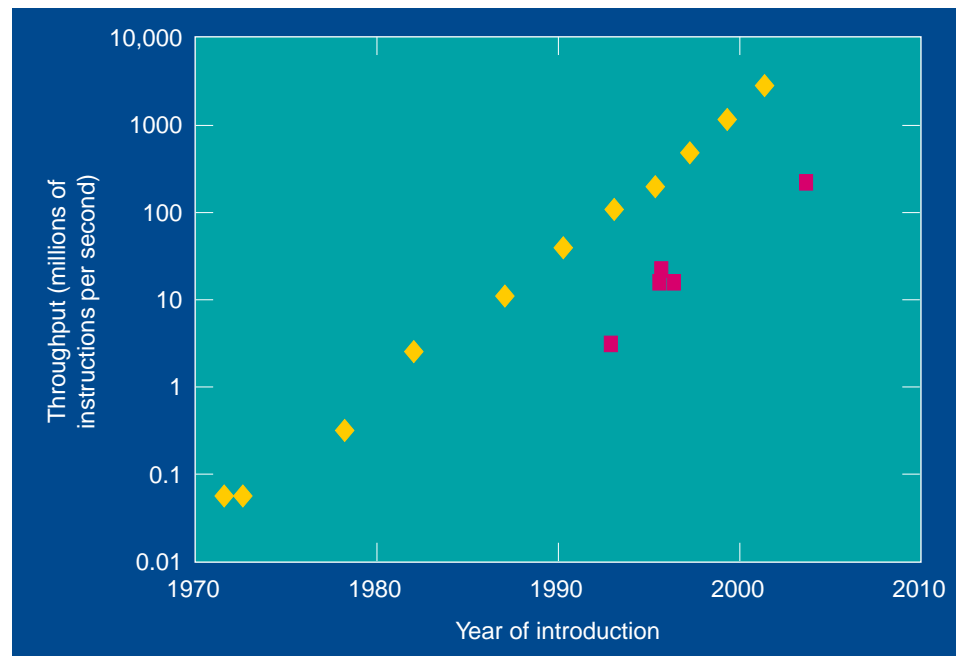
## Testing Total-Dose Hardness

The Aerospace microelectronics radiation effects test facility has both a cobalt-60 gamma-radiation source and an x-ray source. This equipment is used in conjunction with semiconductor parameter analyzers and mixed-signal testers to evaluate radiation-induced performance changes in electronic components according to military standards. The facility has been used to test the sensitivity of electronic devices and circuits fabricated for advanced technology programs and spaceflight hardware over total-dose and dose-rate ranges typical of exposure to the natural space environment. Aerospace is using this system to evaluate the total-dose hardness of test structures and other products built at a number of commercial CMOS foundries to assess their potential for space-qualified manufacturing.

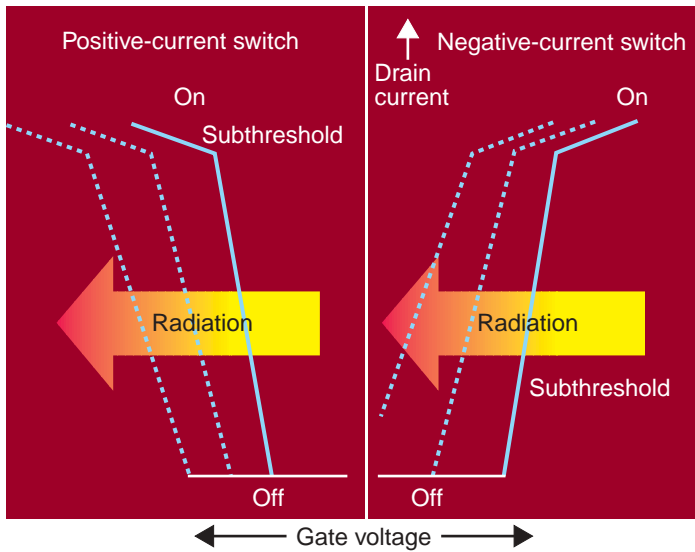
circuit time to recover from a particle strike. Perhaps the most common approach is to use redundant information storage or error-checking circuitry. For example, a technique known as “voting logic” can be used to catch and correct potential errors in latches. With this technique, a single latch does not effect a change in bit state; rather, several identical latches are queried, and the state will only change if the majority of latches are in agreement. Thus, a single latch error will be “voted away” by the others.

Another technique useful for overcoming single-event upsets is known as “error detection and correction.” In this technique, the system architecture provides

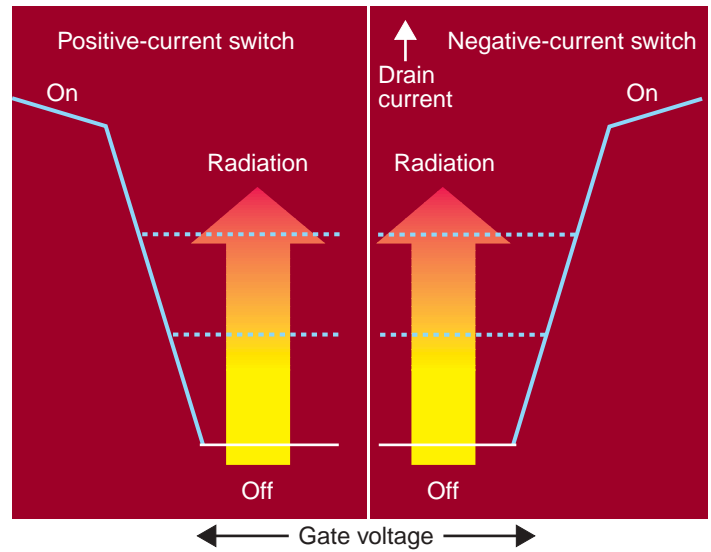
extra check bits in each stored word in memory; when these extra bits are read and interrogated, errors become apparent and can be corrected. Perhaps the simplest approach would be to insert a single bit that denotes whether the content of a word has an even or odd parity; this requires minimal overhead, but does not automatically identify the location of any observed errors. On the other hand, to uniquely detect and correct a single error in a 16-bit word using the common “Hamming code” method requires the insertion of six additional bits. Thus, the error detection and correction technique requires a significantly greater number of memory bits to store a given amount of information.



This graph charts the increasing speed of microprocessors versus year of introduction for commercial products (the diamond plots) and rad-hard products (the square plots). Because of the additional effort and cost associated with developing radiation-hardened processes, the performance of space-qualified electronics has typically lagged by 5 to 7 years behind their nonhardened counterparts. Similar performance lags are seen in memories, application-specific integrated circuits, and other electronic components.



Charge buildup affects the current-voltage characteristics of the transistors used in semiconductor circuits. Proper operation of a transistor relies on the ability to switch it from a low-conductance (off) state to a high-conductance (on) state as the gate voltage passes through a threshold. Extended expo-



sure to radiation can shift the threshold voltages (*left*), making the transistors easier or harder to switch. Radiation may also increase the leakage current (*right*), causing the on and off states of the transistors to become less distinguishable. Either effect can ultimately cause circuit failure.

### Performance Implications

Design-hardened versions of integrated circuits require more space or circuitry than their unhardened counterparts; therefore, overall performance will not be as good. Depending on the specific circuit function and the level of hardness required, the area penalty may vary widely. Different mixes of RHBD techniques can be used to provide elements with a range of hardness

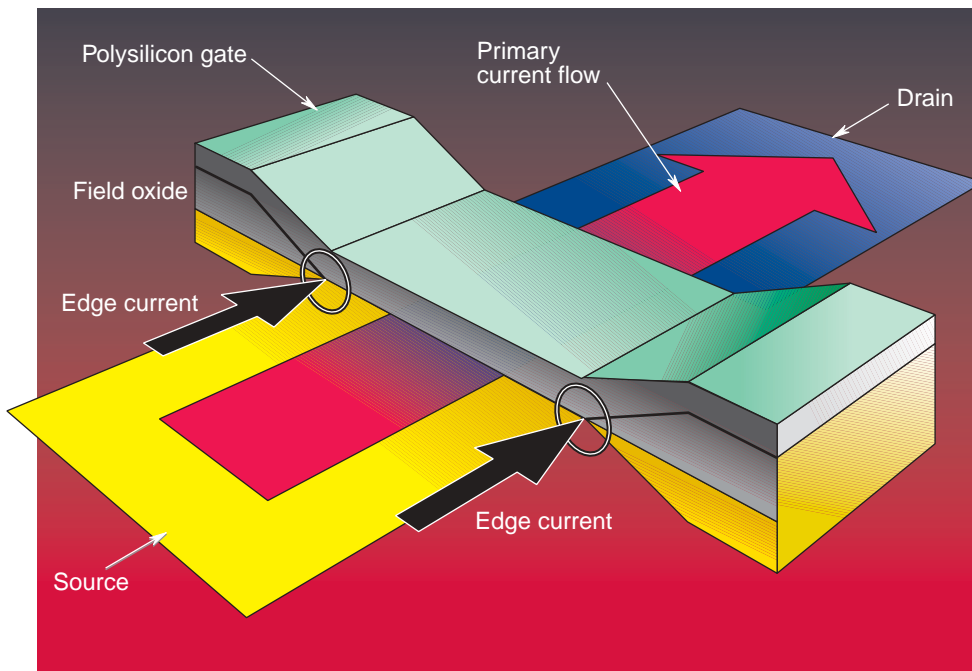
levels, allowing the circuit designer to target different radiation requirements. Critical memory-storage elements such as latches and flip-flops might require hardening against total-dose effects as well as single-event upset. These elements may require redundant transistors and may consume three or four times the area of a conventional element. In fact, the static random-access memory, which contains

primarily storage elements, is the worst-case circuit for the RHBD approach. On the other hand, combinational elements such as logic gates or multiplexers may require only total-dose hardening, with a smaller area penalty, or may even employ commercial designs as is, if the total-dose requirements are modest. The area penalty for a given circuit layout will depend on the overall number of each of these types of elements.

For example, a design-hardened chip using two-, three-, or four-input logic gates with edgeless transistors and guard bands might be several times bigger than a commercial version of the chip. The resulting capacitance increase would cause an increase in power consumption and a reduction in circuit speed, compared with a commercial design using the same technology. But, compared with the same chip from a typical rad-hard foundry, which is assumed to be two generations behind the commercial process, the design-hardened part would show improvements in area, power, and speed.

### Reliability

The shrinking of commercial CMOS technologies has proceeded faster than reductions in supply voltages. As a result, each new generation operates with relatively higher electric fields. This has exacerbated the reliability problems associated with advanced CMOS devices because the higher electric fields can damage materials and



Edge-current leakage in transistors. Current should flow only between the source and the drain when the gate receives a proper voltage; however, after extended exposure to ionizing radiation, current can leak through at the edges, where the gate oxide and insulating field oxide meet.

	Rad hard 0.5 micron	Commercial 0.25 micron	RHBD 0.25 micron
Chip active area	1	0.25	0.81
Max. operating frequency	1	6.5	6.0
Power at max. speed	1	1.4	4.2
Power at constant speed	1	0.22	0.70

Relative performance parameters for a hypothetical 100,000-gate logic circuit (without latches) in unhardened, foundry-hardened, and design-hardened versions. Using a two-input logic gate along with edgeless transistors and guard bands, the design-hardened version (hardened only against total-dose effects) requires 3.2 times more chip area, runs 8 percent slower, and dissipates 3.2 times as much power at constant speed than the commercial version. However, when compared with the same circuit from a typical rad-hard foundry, which is assumed to be two generations behind the commercial process, the design-hardened version requires 29 percent less area, runs 6 times faster, and consumes 30 percent less power at constant speed.

interfaces. Manufacturers of commercial systems have been willing to trade reliability for better overall performance, but designers of space systems cannot accept this trade-off. Space systems require higher reliability because replacement of faulty parts is difficult or impossible after deployment and because component failures may compromise national security. Furthermore, typical service life tends to be longer for military systems.

Various approaches can help mitigate the reduced reliability of advanced CMOS technologies. For example, power-supply voltages can be lowered to reduce internal electric fields in a given circuit. A system-level approach to power management might include controls to cut power to unused circuits or subcircuits, thereby prolonging service life. The use of RHBD techniques offers even more options. For example, the length of critical transistor gates can be increased to reduce electric fields and prolong service life; however,

because these longer transistors are slower than the minimum-size transistors, the increase in reliability comes at the expense of speed. Another alternative is the use of annular transistors to reduce the drain electric field in advanced CMOS devices. An analysis performed by Aerospace has demonstrated that the curvature associated with these annular devices spreads the electric field lines at the high-field end of the transistor, reducing the damage done by energetic carriers.

#### Future Issues

The RHBD approach must demonstrate its ability to consistently and reliably supply a full range of rad-hard parts before it will be accepted as a viable alternative to the dedicated foundry approach. Aerospace is working with the relevant government agencies to create and maintain a coordinated RHBD infrastructure to address all the relevant issues.

For example, circuit designers use computer-aided design tools to define and

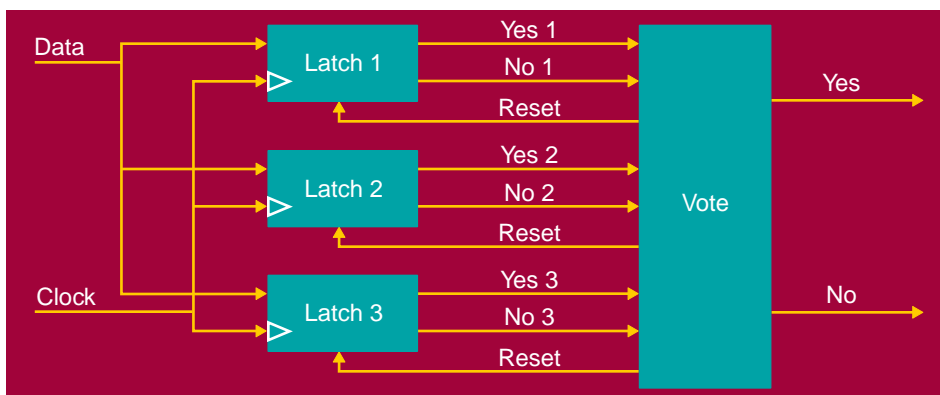
verify the final circuit layout, to perform logical simulation of the design, to identify potential failure modes, and to perform static and dynamic timing simulations. These tools use so-called “cell libraries” to simplify the design process as much as possible. Each library is a collection of individual circuit elements that includes functional and performance information about each element. Effective use of RHBD requires that knowledge of the behavior of the circuits in the space environment be incorporated into the computer-aided design tools. For instance, the programs would need to simulate the electrical behavior of the transistor switch in a radiation environment based on the structure of the device and the physics of the radiation interactions.

Rad-hard cell libraries must be developed and maintained that will include provisions for reliable operation in harsh environments. A number of cell libraries will probably be needed for each CMOS generation to meet the needs of a range of space programs operating in various orbits, and with a range of reliability, survivability, and cost requirements. Funding for libraries with the most stringent requirements—and thus the smallest markets—must be generated by the customer community, most likely the Department of Defense (DOD).

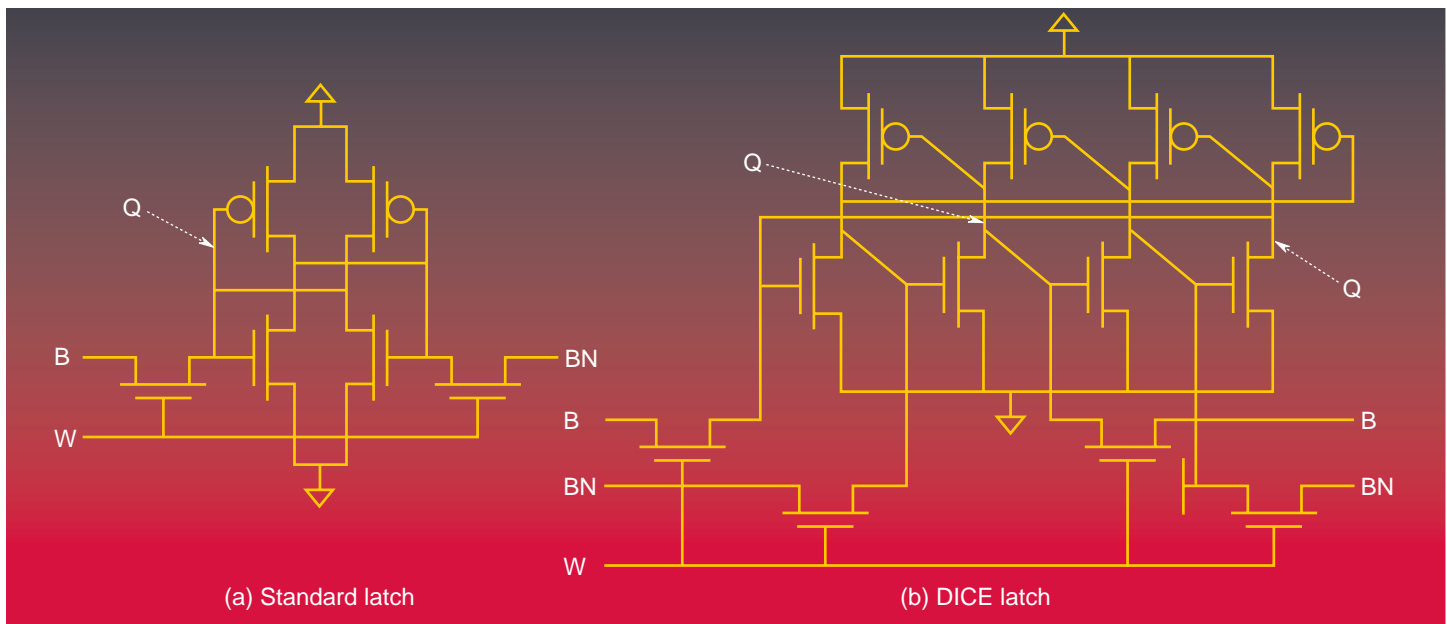
Commercial foundries typically provide the starting material for all electronic components manufactured in their processing facilities; however, nonstandard starting materials incorporating epitaxial layers or insulating substrates, for example, may enhance radiation immunity. The part supplier and the selected foundry may agree to substitute appropriate starting materials to provide additional levels of radiation hardness.

Each foundry typically uses proprietary procedures developed over many years; however, nonstandard processing steps involving, for example, novel implants or modifications of layer thicknesses may help enhance radiation immunity. In an approach known as coprocessing, the RHBD part supplier and the selected foundry may agree to substitute or augment appropriate manufacturing steps to provide additional levels of radiation hardness. This approach has been used successfully by at least one rad-hard component supplier.

Government agencies, corporations, and universities around the world are presently researching and developing RHBD



Potential errors in latches can be caught and corrected using voting logic, in which a majority of the outputs of three identical latches determines the correct output. Two simultaneous errors must occur to produce an error at the output, which is rare in a properly designed circuit.



A six-transistor latch, commonly used as the storage element in a static memory circuit, is shown alongside a design-hardened 12-transistor variant (Calin et al.). “B” and “BN” are the bit lines, used to input and output zeros and ones to the memory cell. “W” represents the word line, used to activate the cell and read out the stored information. In the conventional cell,

a particle strike directly into node Q may cause the latch to change state, resulting in an error. In the design-hardened version, Q is represented at two different nodes. Thus, a strike at any single node cannot cause an upset. The number of transistors per latch has doubled, which can significantly reduce the available gate count in a given circuit area.

techniques. The Air Force Research Laboratory is funding several such projects, including some geared toward developing rad-hard digital and mixed-signal circuits. The Defense Threat Reduction Agency is similarly funding various RHBD efforts, including programs to develop a radiation-tolerant static-memory chip using a commercial foundry, a radiation-hardened readout integrated circuit using both traditional rad-hard foundry processing and RHBD techniques, and a submicron-level chip incorporating RHBD features. The agency is also developing an integrated, foundry-independent rad-hard digital design center and has a program to develop and demonstrate an analog standard cell library.

DARPA (the Defense Advanced Research Projects Agency) has recently announced a major program to develop digital, analog, and mixed-signal circuits in highly advanced commercial technologies using RHBD techniques. Aerospace will play various consulting, testing, and integration roles in this program.

NASA has also been employing design-hardening concepts in various projects. The Europa satellite, for example, will be exposed to more than 6 megarads over the life of the mission. To meet this high total-dose requirement, NASA is using rad-hard processors along with several digital and

analog circuits designed using redundancy and other RHBD techniques.

Aerospace is working with each of the DOD agencies and NASA through the Radiation Hardened Electronics Oversight Council to develop and coordinate a road map that will identify funding needs and opportunities for RHBD cell libraries, design tools, component designs, test facilities, and other aspects of the RHBD infrastructure.

### Summary

Radiation hardness by design has quickly evolved from a laboratory curiosity to a business strategy that may well redefine the way electronic components are procured for defense space systems. Aerospace and others have demonstrated that RHBD techniques can provide immunity from total-dose and single-event effects in commercially produced circuits. CAD tools that can model these radiation effects and cell libraries that use a range of these techniques have been developed at a number of government agencies, universities, and private companies during the past several years, culminating in the commercial production of RHBD memories, microprocessors, and application-specific integrated circuits that are being specified in DOD and NASA missions. The infrastructure needed to make RHBD a mainstream procurement approach is gradually being

developed. Aerospace continues to play a major role in assessing radiation immunity trends in the commercial CMOS sector and in coordinating the development of the infrastructure needed to support RHBD for future space systems.

### Further Reading

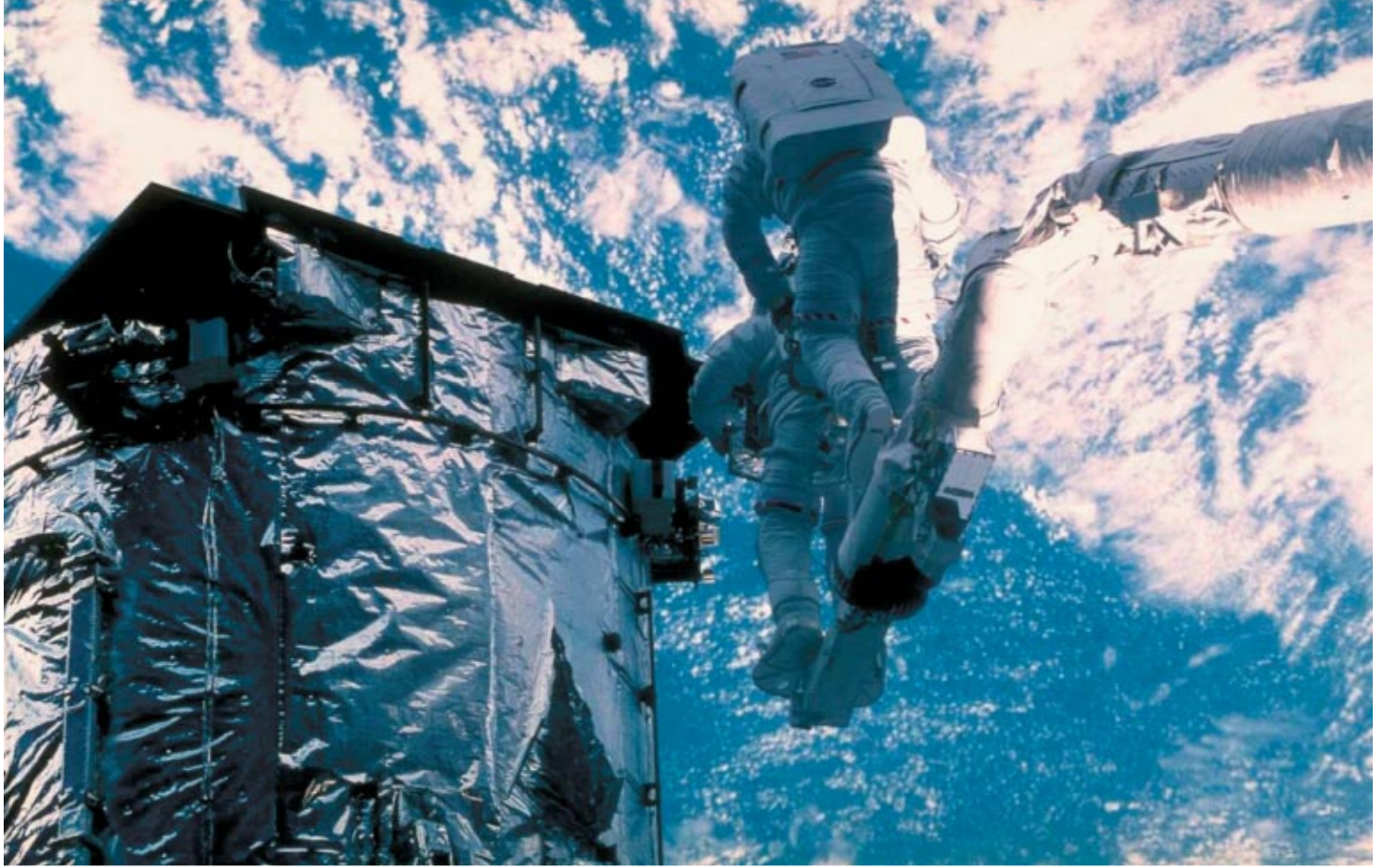
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NASA

# Ground Testing of Spacecraft Materials

Wayne Stuckey and  
Michael J. Meshishnek

*Spacecraft paints, films, and coatings are more than cosmetic—they contribute to the vehicle's thermal design. Ground-based testing can help determine how well and how long these materials will survive the harsh space environment.*

**D**espite its apparent scarcity of matter, the near vacuum of space presents a hostile environment for external spacecraft surfaces. A spacecraft receives the full spectrum of solar radiation, and these electromagnetic waves, charged particles, atoms, and plasmas can cause surface materials to grow dark or brittle, or even erode away. Such changes can lead to increases in spacecraft temperatures or degradation of optical and power-system components. Aerospace has developed environmental models, simulations, and ground-based testing methodologies to identify the most stable materials and provide data that can be used to design spacecraft that can tolerate on-orbit material degradation.

## **Ramifications of Material Change**

Thermal control plays a central role in spacecraft operations. The lack of atmospheric convection in space limits a satellite's ability to dissipate heat. The thermal design must therefore consider how much solar radiation will be reflected or absorbed by external surfaces. In addition, onboard electronics usually generate waste heat that must be dissipated. Reflective paints and thermal-control films can influence the reflection and absorption of solar radiation and the dissipation of heat by emission of infrared radiation. Ideally, these paints and films would not change over time, but both flight experience and ground experiments have shown that they do. Thus, to produce a suitable thermal design, the spacecraft

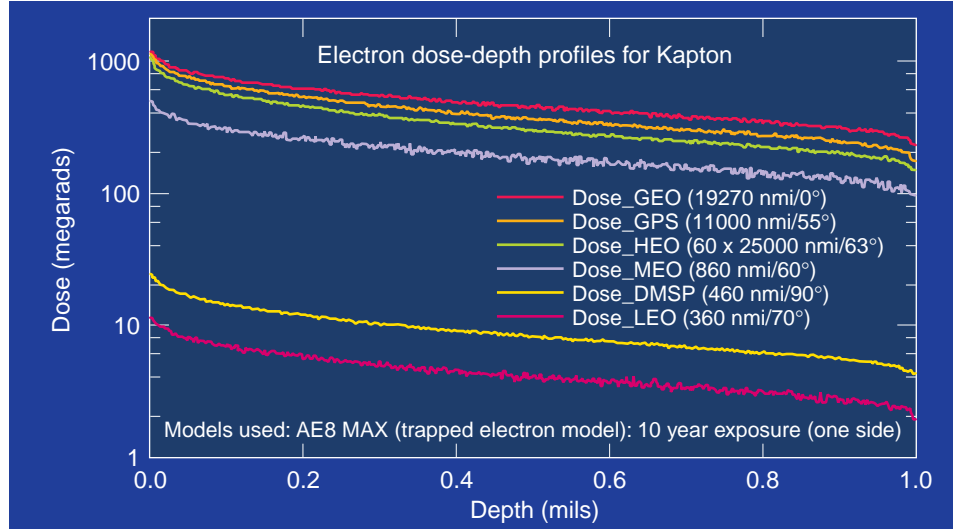
Service mission for the Hubble Space Telescope. The films that are clearly torn to the left of the astronauts are the outer layers of the thermal blankets. Many such areas had to be covered with new material.

developer needs to know what the thermo-optical properties of these materials will be both at the beginning and end of the intended mission.

Various paints are used for spacecraft applications, including polyurethanes, silicones, and silicates, some of which are formulated specifically for space use. The choice of a paint might depend on several factors, including cost and durability. Polyurethanes, for example, tend to be cheaper, but suffer greater degradation on orbit. The silicates are more stable, but are also more expensive, more brittle, and harder to apply. Knowing how different paints will hold up in a particular orbit can help designers choose the best one for meeting cost and performance requirements.

A similar situation exists for thermal-control films, such as Kapton and Teflon. These polymeric films may be applied in single layers to a spacecraft surface or, more often, fastened together as part of a thermal blanket. These films and blankets work the same as thermal-control paints: they insulate and shield components from solar radiation and allow heat generated onboard to be rejected. Thermo-optical properties of the outer layer of these blankets, exposed to the space environment, must be known at the design stage to ensure proper thermal performance for the duration of the mission.

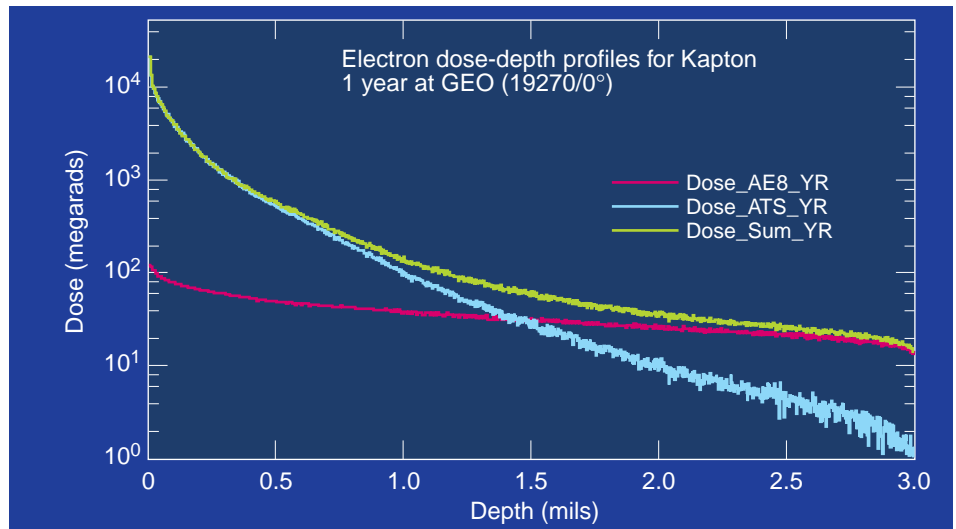
The harsh space environment can also degrade the solar array—a critical component of the onboard power system. Optical coatings, applied to solar-cell cover glasses, are typically used to increase the efficiency of solar cells, and these can grow darker after a long exposure to the space environment. These surfaces almost always face the sun, which means they can also attract and hold outgassed contaminants produced when a satellite settles into orbit. This deposition process involves a photochemical reaction between the surface and the contaminant molecules, causing them to stick irreversibly. Solar-array degradation is of course predicted for the mission lifetime; but such contamination can cause the solar array to degrade much faster than



Ten-year electron dose-depth profiles for Kapton in various orbits. The graph clearly shows the wide range in the deposited radiation dose depending on the orbit. The surface dose is greater than 1 megarad even at low Earth orbit.

anticipated. In some cases, the solar-cell interconnects can also be eroded, eliminating their ability to convey electrical power. Degradation of solar-cell cover glasses from solar radiation and contamination is suspected as the cause of the anomalous Global Positioning System (GPS) solar-array power degradation.

Long-term flight data for films, paints, and optical coatings are not always available, so the spacecraft designer is challenged to select materials that will perform as intended for the duration of the mission. Compounding matters, manufacturers sometimes change their paint formulas, often with unforeseen consequences for



One-year electron depth-dose profiles for Kapton in geosynchronous orbit with the low-energy predictions included. The surface dose is two orders of magnitude higher than that predicted by AE8 alone. The combined depth-dose curve calculated using both the AE8 MAX, and the low-energy ATS plasma electron contribution, are used in Aerospace laboratories for a proper ground simulation.



### The Long Duration Exposure Facility

The Long Duration Exposure Facility (LDEF) was launched by the space shuttle in April 1984 and recovered in January 1990. It housed 57 experiments containing more than 10,000 specimens to test the effects of the space environment on materials, components, and systems. Originally planned for 1 year, the exposure actually lasted almost 6 years.

Aerospace was involved with LDEF from its initial conception and planning. Aerospace researchers designed, assembled, and integrated one of the most comprehensive experiments onboard, M0003, which exposed numerous spacecraft materials, in use or in development, to the low Earth space environment. M0003 was a collection of 20 subexperiments and was a collaboration of Aerospace, Air Force, and Navy laboratories as well as some spacecraft contractors. Aerospace served as principal investigator in addition to having its own experiments onboard. When LDEF was brought back to Earth, Aerospace documented and disassembled M0003 and analyzed many of the material specimens. There were more than 1275 samples on the M0003 experiment alone.

The data obtained in LDEF analyses have confirmed that most of the models used to predict the effects of the space environment on materials are satisfactory. LDEF generated valuable information on long-term materials performance in orbit and provided significant insights into spacecraft thermal control, contamination control, and the combined effects of ultraviolet radiation and atomic oxygen on spacecraft materials.



space durability. In such cases, ground-based testing is required, but such testing first requires an adequate model of the space radiation environment—and the details of this complex environment are still being explored.

### Ground Test Design

The solar spectrum that propagates through space is not the same as the atmospherically filtered spectrum that reaches Earth's surface. For example, the shorter-wavelength, higher-energy vacuum ultraviolet rays do not penetrate Earth's atmosphere, but these can be the most damaging to spacecraft materials. Including this radiation is only one of the challenges in a ground test of space environment effects.

The electron and proton particle populations are also difficult to simulate. These particles range in energy from a few electron volts to millions of electron volts, with densities that vary widely depending on the orbit. The energy level of a particle will dictate how it reacts with a material, determining whether it will effectively "bounce off" the surface, become buried in the surface layers, or deposit its energy deeper into the material. Recent improvements in space-environment modeling with a more complete consideration of low-energy contributions to the total radiation environment, and the inclusion of these models with particle energy transport codes, have led to better approaches to ground simulation.

The low-energy or plasma portion of the spectrum is especially significant for surface materials such as thermal-control paints and coatings, exposed optics and their coatings, multilayer insulation, solar-cell cover glasses, uncoated thin structures, and some inflatable structures. These materials encounter the full force of the space environment, while most electronics or other materials are, in effect, shielded by the spacecraft itself. A ground-based simulation test of surface materials in high-radiation environments must include this part of the spectrum as well as the higher-energy part of the spectrum.

The Van Allen radiation belts present different hazards for different orbits. The lower belt is dominated by protons, while the upper belt is predominantly electrons. A low Earth orbit generally stays below the proton belt but still passes through it at some point in its orbit. A geosynchronous satellite is primarily affected by the outer radiation belt. The highly elliptical and medium Earth orbits spend a considerable



amount of time in both belts. In addition, a satellite in low Earth orbit can encounter high levels of atomic oxygen, formed by sunlight splitting oxygen molecules into constituent atoms. Atomic oxygen is highly reactive and can steal atoms of carbon, hydrogen, nitrogen, and other elements from material surfaces, eroding them layer by layer. Clearly, then, the first consideration in the design of a test is the definition of the orbital parameters, and hence the environment that the spacecraft will encounter.

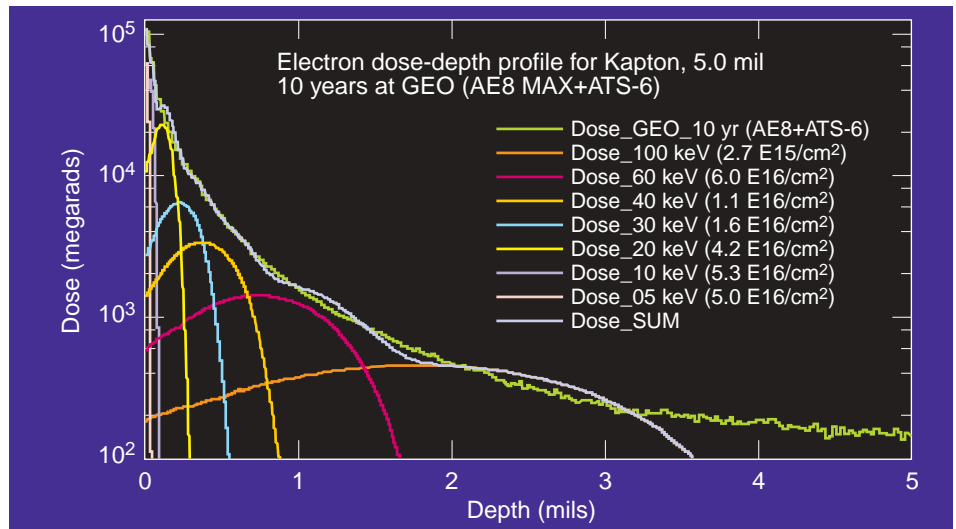
### Predictive Models

Radiation levels change by orders of magnitude depending on the particular orbit. For example, the integrated fluence of trapped protons is four orders of magnitude higher in a geostationary orbit than in a low Earth orbit. The fluence for a medium Earth orbit is even higher. In general, the low-energy plasma environments are not as well known as the trapped radiation environments.

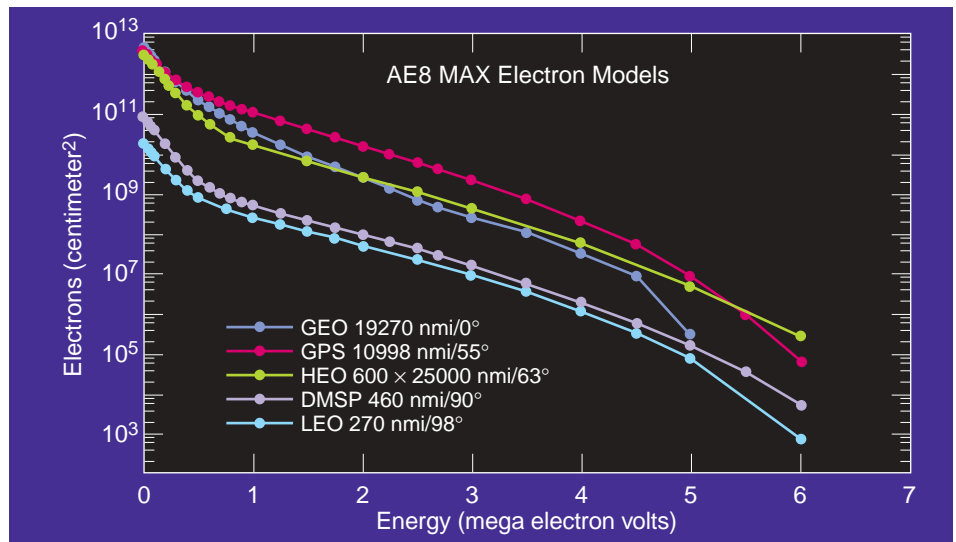
The most commonly used models for estimating particle fluxes are known as AE8 and AP8. Based on flight data, these statistical models were developed by Aerospace (the "A" stands for "Aerospace") and are used extensively by the space community. AE8 MAX and AE8 MIN model electron flux conditions at solar maximum and solar minimum, respectively. Similarly, AP8 MAX and AP8 MIN model proton fluxes as solar maximum and minimum.

The AE8 paradigm allows spacecraft designers to calculate the total radiation dose deposited in a material in a specified orbit. Different materials will absorb radiation in different ways, depending on their density and chemical composition. Thus, the composition and density of the material is used, together with the predicted electron spectrum and fluence, to generate a so-called dose-depth curve for that material. The result is a prediction of the absorbed radiation dose, expressed as rads, versus material thickness or depth that is expected for a specified time on orbit. This prediction can then be used to design a simulation test.

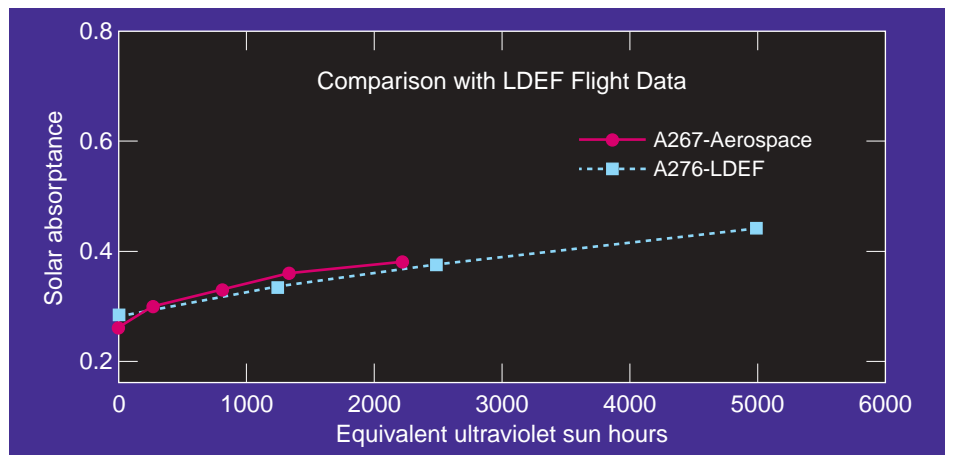
The AE8 MAX dose-depth curve for Kapton, for example, shows a wide range in the absorbed radiation dose depending on the orbit, but even at low Earth orbit, the total deposited surface dose is greater than 1 megarad. For comparison, a dose of 400 to 450 rads is fatal to humans. Any materials exposed on the surface must be able to



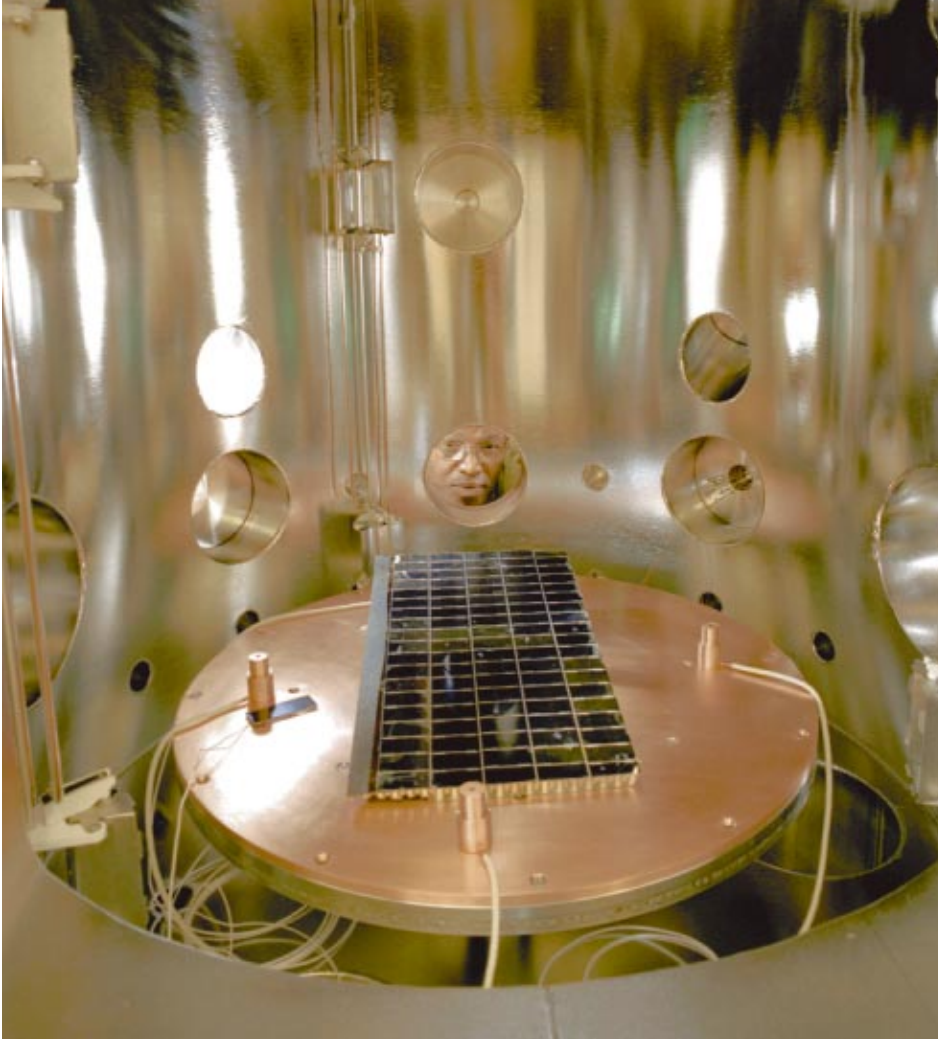
These electron radiation dose profiles for Kapton in geosynchronous orbit were calculated using both AE8 MAX and ATS-6 models. At 40 keV, the peak in the dose-depth curve occurs at about 0.3 mil and does not penetrate significantly beyond 1 mil. At low energies, 10 keV, for instance, the dose might be close but only at about 0.1 mil. A combination of energies is the only way to reproduce the complete dose-depth curve.



Plots from AE8 MAX of the electron fluence as a function of energy for various orbits. AE8 MAX represents the predictions at a period of maximum solar activity. The significant difference in levels between low and high orbits is illustrated. As shown, the number of electrons increases sharply at lower energies. The low-energy part of the spectrum is very important for surface materials.



Data from the Long Duration Exposure Facility (LDEF) mission confirmed the usefulness of Aerospace environmental testing methods. In this graph, the solar absorbance of the white polyurethane paint is plotted as a function of years on orbit. Simulated data corresponds closely with observed data.



The Space Materials Laboratory space simulation chamber can accommodate large samples for testing—even a part of a solar array, as shown in this photograph.

tolerate radiation levels many orders of magnitude higher than any electronic device (which would be shielded). Typical damage thresholds for most polymeric materials are in the 0.1–100 megarad range. Most polymers should be able to survive a

low Earth orbit but may be susceptible to damage at higher orbits.

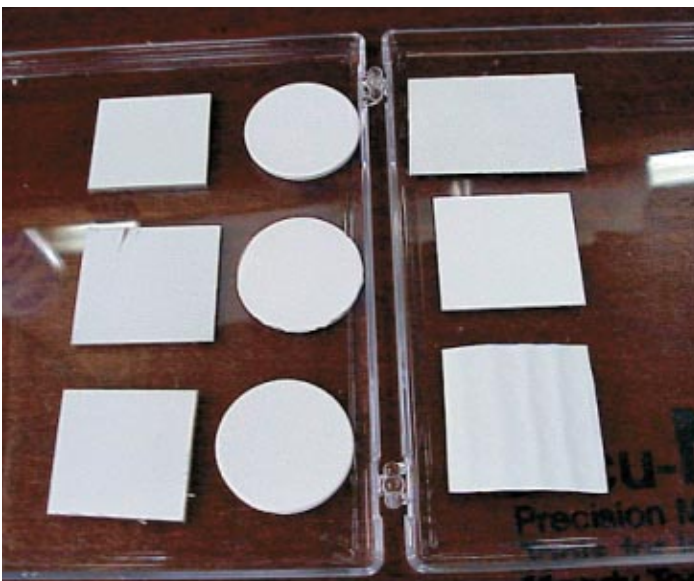
The AE8 algorithm indicates that at any orbit, low-energy electrons (which are most important for surface effects) will be far more prevalent than high-energy electrons.

Nonetheless, AE8 does not adequately model this environment and was never designed to do so. In fact, generally applicable plasma models are not available, especially for low Earth and highly elliptical orbits, though data from the SCATHA (Spacecraft Charging At High Altitudes) ATS-5 and ATS-6 experimental satellites have been used to model the geosynchronous environment. Significantly, a 1-year dose-depth curve for Kapton in geosynchronous orbit using both AE8 and ATS-6 data shows the surface dose to be two orders of magnitude higher than the curve plotted using AE8 alone. Thus, Aerospace now uses combined AE8 and ATS-6 dose-depth curves to generate ground simulations.

### From Models to Test

The problem of simulating the space environment in the laboratory is one of attempting to reproduce the myriad of particle energies and fluxes along with the wide spectrum of radiation emitted from the sun. As for solar radiation, the spectrum of interest—the vacuum ultraviolet, ultraviolet, and visible wavelengths—can be simulated appropriately using xenon and deuterium arc lamps together. The charged particle spectrum is another matter, because the energy of the particles varies so significantly. Simulating this environment is done by calculating the *effect* of all of the fluxes and energies (through a dose-depth curve) and then mimicking this energy deposition with several selected energies and fluences.

Thus, to simulate a space environment dose-depth curve in the laboratory, a combination of electron energies must be



Samples of commonly used white paints were exposed to simulated radiation environments. The paints started out pure white, as in the photo on the left.



right. After a simulated 10-year exposure in geosynchronous orbit, the paints turned brown, as shown in the photo on the right.

selected that will reproduce the on-orbit curve as closely as possible. For example, the dose-depth curve for Kapton in geosynchronous orbit shows that the peak penetration depth for a 40-keV electron is approximately 0.3 mil and that these particles do not penetrate significantly beyond 1 mil. A simulation using a 40-keV electron beam would come close to matching the total on-orbit dose at 0.3 mil, but would not adequately reproduce the dose absorbed at any other depth. Similarly, a low-energy simulation—10 keV, for instance—might approximate the dose absorbed at about 0.1 mil, but not deeper. A combination of energies is the only way to reproduce the complete depth-dose curve. The 100-keV electrons penetrate to a depth of about 4 mils, more than adequate for surface phenomena. Higher-energy electron irradiation—up to 1 MeV—can be used for bulk damage at depths beyond 5 mils where the dose-depth curve is nearly flat. Irradiation using 1-MeV electrons only would never be capable of an acceptable simulation for surface materials because of the mismatch to the surface areas of the curve. The dose from a single energy can be matched at one point on the curve but can never match the complete dose-depth profile.

### Flight Data Comparison

The true measure of any ground test methodology is how closely results agree with flight data. Flight data are not available for as many different materials and for as many different orbital exposures as designers might like, but there are some cases where ground and flight data can be compared. The space shuttle, for example, has returned numerous samples to Earth from the Solar Max satellite, the Hubble Space Telescope, various shuttle-based experiments, and the Long Duration Exposure Facility (LDEF). All of these samples came from low Earth orbits, where the electron and proton populations are low, but where ultraviolet and atomic-oxygen levels are high. On-orbit exposure time for these samples varied, with LDEF providing the longest exposure of 69 months.

For other orbits, data are sometimes transmitted back to Earth that provide insight into materials degradation. For example, the geosynchronous SCATHA satellite has provided data on a few commonly used spacecraft materials. SCATHA identified radiation effects such as surface and bulk charging, attraction of

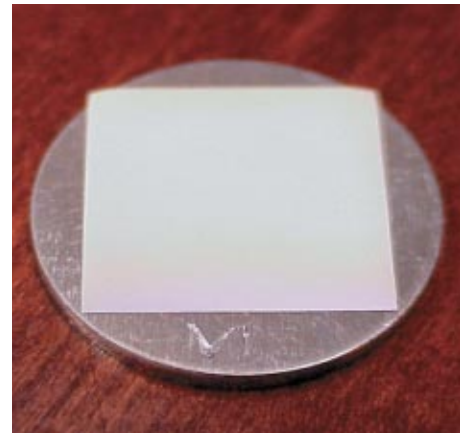
outgassed contaminants by charged surfaces, radiation-induced conductivity of dielectric materials, and deterioration of thermal-control materials and coatings. Aerospace experiments on SCATHA included thermal-control materials like silver Teflon. Other experiments flown on the Defense Support Program and GPS spacecraft have also provided data on paint degradation in high-radiation environments.

Overall, Aerospace simulations match flight-test data fairly well. For example, in ground tests, white paints turned brown after a simulated 10-year exposure to the solar ultraviolet, electron, and proton environment encountered in a geosynchronous orbit. The color change represents an increase in the solar absorptance—which can lead to unacceptable increases in spacecraft temperatures, if not anticipated in the thermal design. Similarly, white polyurethane paints on LDEF had already turned brown when the satellite was retrieved. The change in solar absorptance, as measured by a spectrophotometer, was consistent with Aerospace predictions from ground testing.

Another ground study exposed Tedlar (a white film made from a fluoropolymer) to two different simulated orbital environments. The samples had an ultraviolet rejection coating to block the most damaging part of the ultraviolet spectrum. The samples exposed to a low Earth environment, where the radiation levels are not high, remained relatively stable; however, the samples exposed to geosynchronous conditions degraded severely, becoming shredded and cracked. Researchers attributed this effect to the penetration of high fluxes of low-energy electrons through the thin coating, causing degradation of the Tedlar polymer.

### Conclusion

The agreement between Aerospace tests for the low Earth orbit environment and data from the LDEF experiment is good. Similarly, data from SCATHA support predictions based on laboratory models of the geosynchronous realm. This agreement with flight data gives confidence that ground tests are providing reliable data for the performance of materials in space. More important, such ground simulations enable Aerospace to make straightforward recommendations to satellite designers to ensure that all materials used will be suitable for a given mission. 🌍



Samples of Tedlar, a white fluoropolymer film, were exposed to simulated radiation environments for various satellite orbits. Supplied with an ultraviolet rejection coating to block the most damaging part of the ultraviolet spectrum, the samples started out bright white, as in the top photo. When exposed to a simulated low Earth orbit, the material remained relatively stable, exhibiting only small changes. However, after a 1-year simulated exposure to a geosynchronous orbit, the samples turned a purple-brown color, as in the middle photo. Such a color change increases the solar absorptance, which can lead to unacceptable increases in spacecraft temperatures. After a simulated 3-year exposure in geosynchronous orbit, the Tedlar samples became severely degraded and would have been useless for any space application, as shown in the bottom photo.

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- H. T. Yura and L. Thrane, "The Effects of Multiple Scattering on Axial Resolution in Optical Coherence Tomography," *Conference on Lasers and Electro-Optics* (Long Beach, CA, May 19-24, 2002), Vol. 1, p. 476.

## Patents

- A. Abbott and W. Lillo, "Global Positioning Systems and Inertial Measuring Unit Ultratight Coupling Method," U.S. Patent No. 6,516,021, Feb. 2003.

This "ultratight" coupling technique provides a method of tracking GPS signals from within an aircraft or missile using a correlation process based on the best estimate of the vehicle's vector. A group of Kalman prefilters and a Kalman integration filter generate this vector estimate. The Kalman filters combine measurements from the inertial measurement unit of the onboard inertial navigation system with ephemeris data from a GPS satellite. They then generate replica signals for correlation with the received GPS signals for determining pseudorange and pseudorange-rate residual errors. These replica signals are in turn used to update

the vehicle's vector information for the next major cycle, which generates the replica signal for the next major cycle, and so on. The closed, coupled tracking loops offer better tracking of the received GPS signal than do traditional methods.

- H. G. Campbell, R. E. Hovden, G. W. Law, "Janus Reusable Spacecraft System," U.S. Patent No. 6,446,905, Sep. 2002.

A spacecraft launching system having two identical reusable vehicles, one of which serves as a booster stage and the other as an orbiter, reduces the cost and complexity of reusable launch systems. Both vehicles have identical flight-control and propulsion systems. Identical payload bays provide space for mission-specific payloads on the orbiter and room for a removable tank on the booster (for a substantial amount of additional propellant). Selected standardized components may also be added or deleted as required for each flight. The use of identical boosters and orbiters reduces overall cost because only one stage of this two-stage launch vehicle need be developed. Launch operations are simplified because only one type of stage needs to be checked and refurbished after landing.

- S. J. DiMaggio and B. H. Sako, "Rocket Engine Gear Defect Monitoring Method," U.S. Patent No. 6,526,356, Feb. 2003.

This screening method uses vibration and tachometry measurements to detect anomalous gear performance in rocket-engine turbo machinery before launch. It is based on a two-sided cepstrum analysis, defined as the inverse discrete Fourier transform of the logarithm of two-sided autospectral density. Vibration measurements are acquired during static hot fire tests from accelerometers mounted on the gearbox of the rocket engine. The cepstrum analysis then identifies which turbopumps functioned normally and which exhibited anomalous vibration signatures, based on the known parameters for that family of engines. Measurements acquired during ground testing can be converted into parameters that are indicative of anomalous behavior. These parametric results can then be used to assess the possible presence and progression of a gear-tooth fault in the gear train.

- P. D. Fuqua and J. D. Barrie, "Tunable Solid State Thin Film Optical Filter," U.S. Patent No. 6,522,469, Feb. 2003.

Manufactured using conventional thin-film deposition processes, this solid-state optical filter provides highly accurate passbands with a degree of tunability. The design includes a thin-film electrooptical dielectric with a voltage-controlled refractive index sandwiched between two optical-interference stacks composed of films with alternating refractive indices. A tuning voltage applied to the optical interference stack shifts its spectral features, such as the transmission passband, by a predetermined amount. Passband tuning occurs without moving any of the elements; as a

result, the optical filter is robust and vacuum compatible. The device is insensitive to polarization and reflects energy not transmitted. It has many applications, including multiplexing and demultiplexing of optical signals.

- G. F. Hawkins, "Adhesive Strengthening Embedded Micromachines," U.S. Patent No. 6,588,969, July 2003.

Microminiature levers can be embedded in an adhesive film prior to curing to increase the shear strength of a bond. The embedded levers are designed with an irregularly shaped cross section, such as a trapezoid. Thus, they tend to rotate under shear loads. The rotation causes the top and bottom faces of the microlevers to compress the adhesive film. Thus, the adhesive is simultaneously under the influence of both shear and compressive forces. The compression eliminates the tensile stress typically present in bondlines, which consequently eliminates peel stresses. Substantially identical microlevers can be embedded inline in an adhesive film so that several levers rotate concurrently for uniform compression along the adhesive bondline.

- D. A. Ksienski and G. M. Shaw, "Intermodulation Grating Lobe Suppression Method," U.S. Patent No. 6,496,158, Dec. 2002.

Developed for radio-frequency communication systems, this technique improves signal transmission by a phased-array antenna by reducing the strength of intermodulation grating lobes (a type of signal interference) in the antenna's field of view. The design is based on regular spacing of subarrays, each of which contains several phased-array antenna elements that are also regularly spaced. Two modulated carrier signals are generated at two frequencies. These are then phase shifted into two sets of signals, which are then summed and amplified, creating intermodulation products in the intermodulation grating lobe beams within the field of view. The regular spacing of the subarrays and antenna elements generates a null in the antenna pattern, which can be positioned upon the intermodulation grating-lobe beams.

- L. Kumar and R. K. Douglas, "Unambiguous Integer Cycle Attitude Determination Method," U.S. Patent No. 6,587,761, July 2003.

The method uses GPS signals to determine the attitude reference of a moving vehicle (such as a spacecraft). Three receiving antennas—one master and two slaves—are equipped with GPS receivers and positioned to achieve carrier-phase alignment of GPS signals. This allows the controller to determine coelevation and azimuth angles to the GPS satellites; this information can in turn be used to determine the attitude of the vehicle in an inertial frame of reference from known GPS satellite lines of sight. The antennas are orthogonally aligned and controlled to allow the slaves to rotate around the master as well as undergo linear dither motion. A fractional phase of the GPS carrier signal received by the slaves is meas-

ured relative to that received by the master. The measured carrier signal is processed to eliminate the integer-cycle ambiguity for determining the attitude reference by computing two noncolinear line-of-sight vectors. The method can be used to determine more than one noncolinear unit vector along the lines of sight from the master antenna to GPS satellites functioning as pseudo stars.

- E. Y. Robinson, "Spacecraft Solar Panel Spherical Trickle Charger," U.S. Patent No. 6,511,022, Jan. 2003.

This spherical solar-panel array—or "PowerSphere"—serves as a backup power source or trickle charger for spacecraft auxiliary batteries. In contrast to conventional solar arrays, the device does not require controlled orientation toward the sun. When deployed, it collects power whenever it's illuminated—even when the main flat-panel solar arrays are positioned edgewise to the sun and therefore unable to collect solar power. The PowerSphere is composed of lightweight thin-film solar cells that are deployable into suitably large structures. It can be used to supplement conventional solar arrays, ensuring that the spacecraft can generate at least enough power for communications and corrective action in case the primary solar panels fail to produce sufficient energy.

- E. Y. Robinson, M. H. Abraham, P. D. Fuqua, "Lateral Exhaust Microthruster," U.S. Patent No. 6,494,402, Dec. 2002.

A microthruster for maneuvering miniature satellites in orbit includes a solid-propellant charge or fuel cell connected to an ignition circuit mounted on a thin diaphragm. Upon ignition, the diaphragm bursts, and the fragments get trapped in a plenum that allows combustion to progress and pressure to build up. The exhaust flows through one or more lateral ports and enters a converging/diverging nozzle; it is finally expelled at the top of the microthruster at a well-defined expansion ratio, producing a controlled thrust vector. The path of the exhaust flow prevents expulsion of the burst diaphragm fragments. The thrust impulse is consistent in magnitude and direction thanks to the efficient conversion of propellant energy.

- P. L. Smith, "GPS Airborne Target Geolocating Method," U.S. Patent No. 6,535,816, March 2003.

This invention describes a method for relative GPS navigation and targeting. A high-altitude aircraft emits a reference beacon. A low-altitude aircraft detects both the beacon and the target. Both the high-altitude and low-altitude aircraft use the same four GPS satellites and therefore have approximately the same GPS positioning errors, which largely cancel out in the targeting solution. This allows the low-altitude aircraft to accurately determine the relative GPS target coordinates for accurately guiding a maneuvering GPS-guided weapon toward the target.

## An Overview of the Space Radiation Environment

**Joseph E. Mazur** is Research Scientist and section manager in the Space Sciences Department. He joined Aerospace in 1997 and is active in the design and construction of advanced particle detectors and the analysis of effects of the space environment on space systems. He is a coinvestigator on two NASA space science missions and has authored or coauthored more than 40 scientific publications on interplanetary and trapped energetic particles. He is a member of the American Geophysical Union and an associate editor of *Geophysical Research Letters*. He holds a Ph.D. in physics from the University of Maryland (joseph.mazur@aero.org).



## What Could Go Wrong? The Effects of Ionizing Radiation on Space Electronics

**Allyson D. Yarbrough**, Principal Director, Electronics Engineering Subdivision, leads an organization of nearly 80 employees with expertise applicable to electronics design, modeling and simulation, rapid prototyping, parts management, failure analysis, anomaly resolution, power-systems engineering, electromagnetic compatibility, and on-orbit vulnerabilities. Prior to joining Aerospace in 1989, she served on the Electrical Engineering faculty at California State University, Los Angeles, and held positions at Hewlett-Packard, IBM, and the Arecibo Radio Astronomy Observatory. She earned a Ph.D. in electrical engineering at Cornell University. She holds five patents and is recipient of the Women of Color Technology Award for Career Achievement (allyson.d.yarbrough@aero.org).

**John Scarpulla** is Senior Scientist in the Electronics and Photonics Laboratory. He recently returned to Aerospace

after working for Northrop Grumman Space Technology, where he focused on reliability and radiation effects related to advanced integrated circuits. Prior to that, he worked at Texas Instruments/Silicon Systems, investigating hot-carrier and electromigration reliability issues for mixed-signal semiconductors. At Aerospace from 1990 to 1995, he was primarily responsible for radiation-effects testing and analysis and first proposed the approach now known as “radiation hardness by design.” He has also worked



at SAIC, GE, and RCA, where he performed radiation testing for the Minuteman and MX missile programs as well as hardened circuit design and analysis. He has an M.S.E.E. from the University of Pennsylvania and a Ph.D. in electrical engineering from Cornell University (john.r.scarpulla@aero.org).

## Picosecond Lasers for Single-Event Effects Testing

**Steven C. Moss** is Director of the Microelectronics Technology Department. He also studies radiation effects on microelectronic and optoelectronic devices and materials, investigates ultrafast phenomena, and develops lasers and optical systems. He received an M.S. in physics from Purdue University and a Ph.D. in physics from North Texas State University. He was a National Research Council postdoctoral research associate at the Naval Research Laboratory and visiting assistant professor at North Texas State University prior to joining Aerospace in 1984 (steven.c.moss@aero.org).

**Stephen D. LaLumondiere** has extensive experience with lasers, optics, and electrooptic systems, as well as

digital and analog microelectronics. His research activities include pulsed-laser testing of microelectronics for single-event effects, analysis of on-orbit radiation effects on Milsatcom systems, and analysis of radiation effects on advanced charge-coupled devices. LaLumondiere received an A.S. in laser and electro-optics technology from Vincennes University in 1988, when he joined Aerospace (stephen.lalumondiere@aero.org).



## Heavy-Ion Testing for Single-Event Effects

**Susan Crain** came to work at Aerospace in 1982 and has participated in various radiation-effects testing programs over the years. She became the lead engineer for the single-event effects testing program in 1995 and has been heavily involved with the testing since then. She also designed single-event effects experiment boards for the Microelectronics and Photonics Test Bed and the Electronics Test Bed on



STRV-1 d. She holds a B.S. in engineering from California State University, Northridge (susan.crain@aero.org). **Rocky Koga** is Distinguished Scientist in the Space Science Applications Laboratory. Since joining Aerospace in 1980, he has investigated the effects of protons, neutrons, and heavy ions on microcircuits and space systems. In studying radiation effects, he has conducted single-event effects tests and experiments at various accelerator sites,



including Lawrence Berkeley National Lab, where various single-event phenomena have been discovered. Through those investigations, he has supported the Milstar, Atlas, Titan, IUS, GPS, and other space programs as well as various NASA programs. He has a Ph.D. in physics from the University of California, Riverside (rocky.koga@aero.org).

### Designing Integrated Circuits to Withstand Space Radiation

**Ronald C. Laco**, Senior Scientist, Laboratory Operations, is responsible for issues related to the effects of radiation on microelectronic components for space systems. He joined Aerospace in 1987 and has performed research and supported various Air Force



programs in the areas of electronic-device and infrared-detector technologies. Prior to joining Aerospace, he worked at Hughes Research Laboratories, developing electrooptical devices. He spent two years with a missile-defense program office, where he was responsible for sensor system definition. Later, as manager of the Microelectronics Reliability and Radiation Effects Section, he focused on the radiation-hardness of commercial microelectronics processes and developed an approach for insertion of hardened-by-design components into military space systems. He holds a Ph.D. from the University of California, Los Angeles (ronald.c.laco@aero.org). **Donald C. Mayer**, Director, Space Electronics Vulnerability Office, pro-

vides coordinated support to a variety of DOD and NASA programs involving the design and manufacture of electronic components for the space environment. He has more than 25 years of experience in microelectronic technologies for space applications. He has also been a visiting lecturer in electrical engineering at UCLA for more than 15 years. He holds an M.S. in physics and a Ph.D. in electrical engineering from the University of Michigan. He has been with Aerospace since 1989 (don.mayer@aero.org).

### Ground Testing of Spacecraft Materials

**Wayne K. Stuckey** joined the Aerospace Materials Sciences Laboratory in 1966. He became manager of the Analytical Methods Section in 1976 and head of the Materials Analysis Department in 1982. He was subsequently named Research Scientist and Senior Scientist in the Mechanics and Materials Technology Center. He was selected as a Distinguished Scientist of the Space Materials Laboratory in 1999. He participated in the Effects of Oxygen Interaction with Materials experiments and was a member of the Long Duration Exposure Facility (LDEF) Space Environmental Effects on Materials Special Investigation Group. He also served as investigator on the M0003 Space Environmental Effects on Materials experiment flown

by Aerospace on LDEF. He holds a Ph.D. in chemistry from Kansas State University (wayne.k.stuckey@aero.org). **Michael J. Meshishnek** joined Aerospace in 1981 to work in the Materials Sciences Laboratory. He became manager of the Survivability Section in 1987. He was named Research Scientist in 1993 and Senior Scientist in the Space Materials Laboratory in 2000. His research interests include space environmental effects on materials, testing and modeling of space radiation exposure, and the durability of materials for space systems. He was a participant in the Effects of Oxygen Interaction with Materials experiments and Principal Investigator for the M0003 Space Environmental Effects on Materials experiment, flown by Aerospace on the Long Duration Exposure Facility. He received his Ph.D. in chemistry from the University of California, Santa Barbara (michael.j.meshishnek@aero.org).



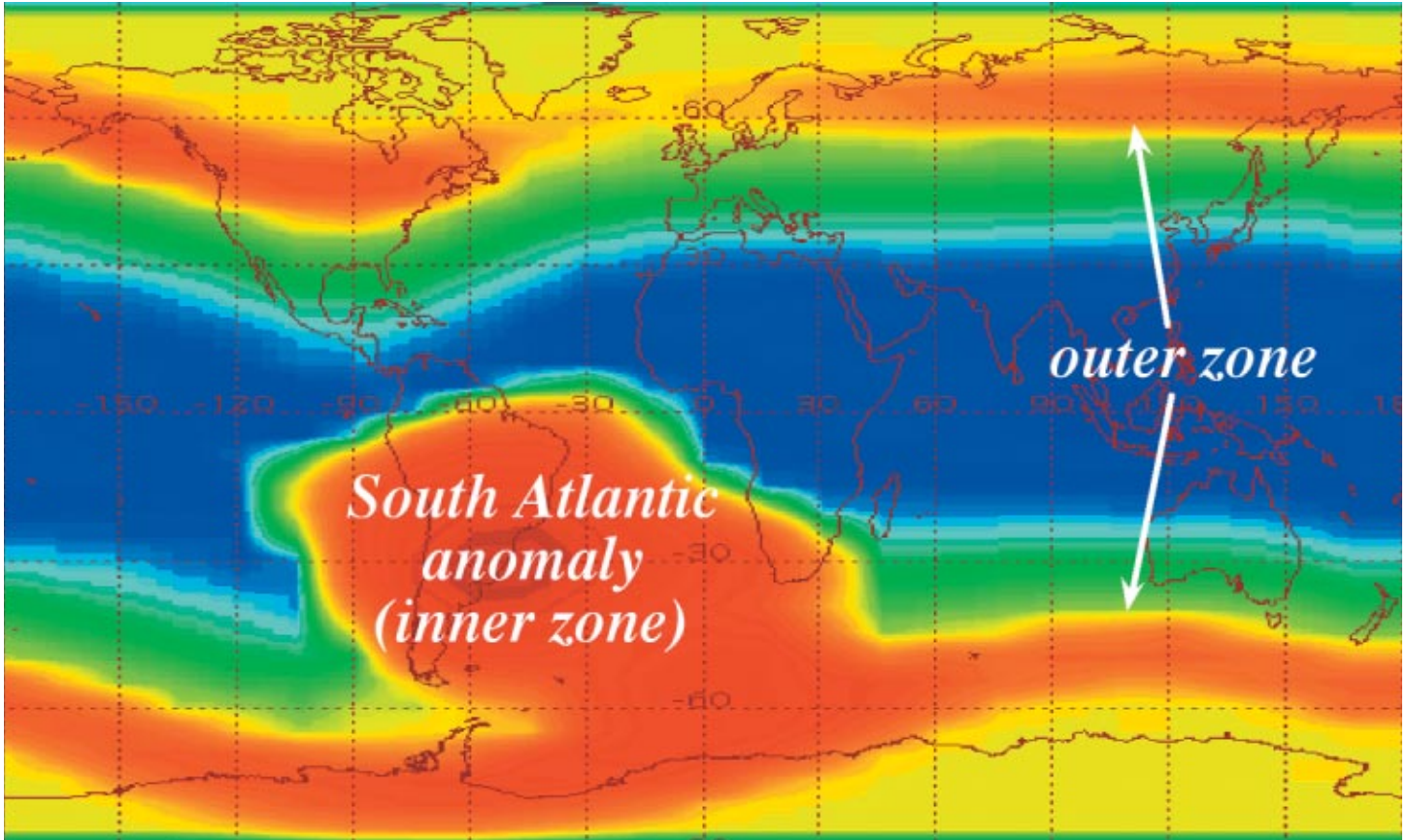
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## A Space Oddity

Gabriel Spera

Count rate of protons and electrons greater than 0.5 MeV in low Earth orbit measured by the NASA/SAMPEX satellite.



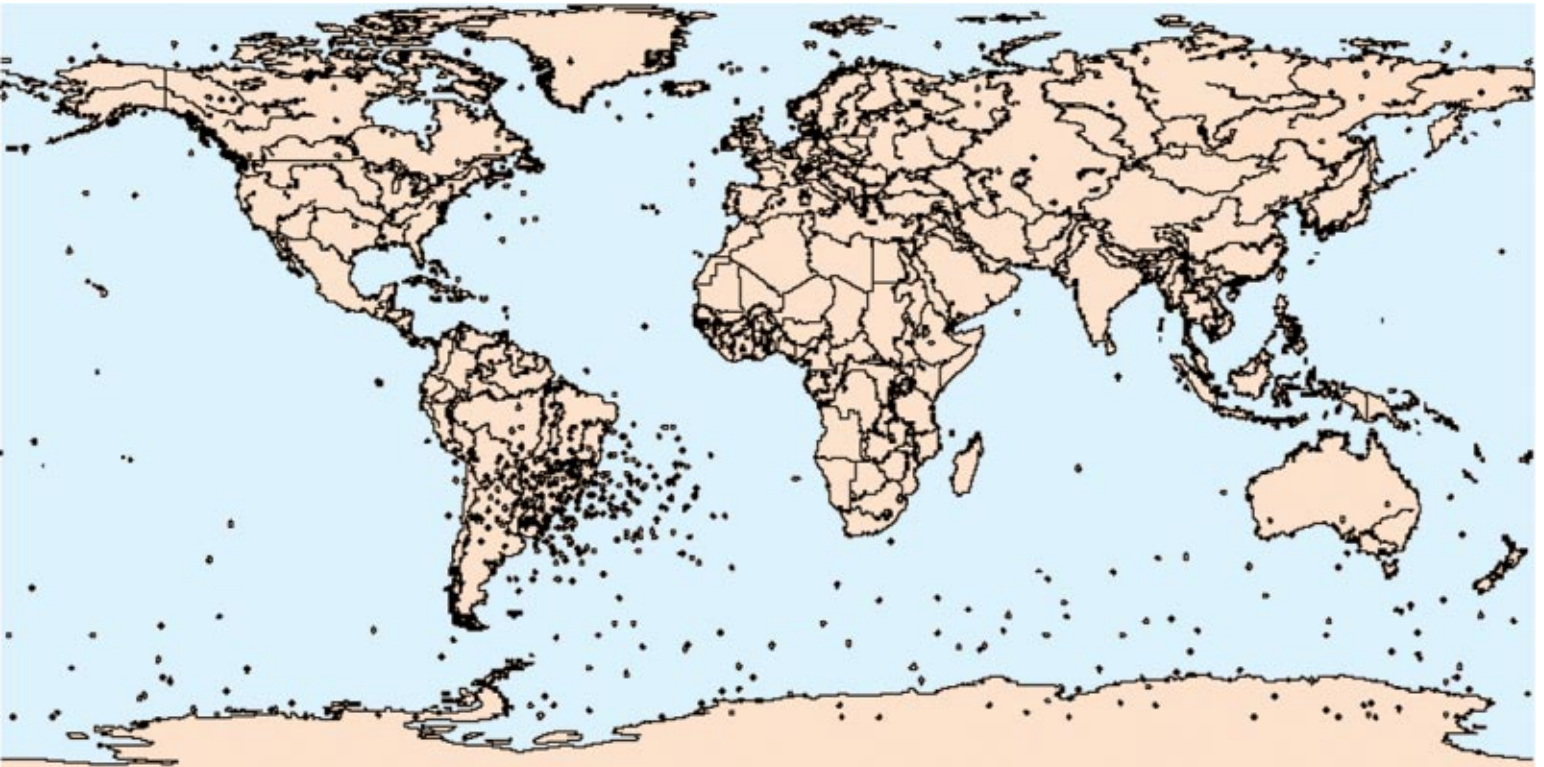
Earth can be viewed as a gigantic bar magnet spinning in space. Its toroidal magnetic field encases the planet like a huge inner tube. This field shields Earth from the solar wind—a continuous stream of charged particles cast off by the sun. It also traps charged particles, which tend to congregate in distinct bands based on their charge, energy, and origin. Two primary bands of trapped particles exist: the one closer to Earth is predominantly made up of protons, while the one farther away is mostly electrons. Evidence of these bands was first made public by James Van Allen, and so they are often referred to as the Van Allen radiation belts. This radiation can cause all sorts of malfunctions in spacecraft electronics. In fact, the Geiger counter used to measure cosmic rays on Explorer 1 stopped functioning because it was overloaded by radiation!

Anyone who has used a compass knows that magnetic north and geographic north do not exactly line up. That's because Earth's magnetic dipole is tilted by about 11.5 degrees from its rotational axis and shifted slightly off-center. At the north magnetic pole, the field is stronger, effectively keeping the inner proton belt farther away; at the south magnetic pole, the field is weaker, allowing the proton belt to come closer to the planet's surface. Most of the proton belt is about 1200–1300 kilometers high, but it dips down as low as 200–300 kilometers off the lower coast of Brazil, creating a phenomenon known as the South American Anomaly. At certain altitudes, the South Atlantic Anomaly is bigger than Brazil itself.

A satellite in a typical low Earth orbit remains safely below the proton belt—except at the South Atlantic Anomaly.

Spacecraft passing through this region are bombarded by protons with energies exceeding 10 million electron volts at a typical flux of 3000 particles per square centimeter per second. These particles can be a hazard for space systems and astronauts.

NASA launched the Terra Earth Observing System spacecraft in 1999 as part of a broad mission to study global climate change. Just one day after launch, the satellite's high-gain antenna spontaneously went into "safe" mode, interrupting communications with the Tracking and Data Relay System satellites. A series of diagnostic tests indicated that an anomalously high current had passed through the motor drive assembly. In fact, there was no high current—only a glitch in a semiconductor component that made it look as though a high current had occurred. This electronic glitch was the result of a single-event upset, an error



Examination of nearly 1300 single-event upsets from one computer on the TAOS mission shows that nearly 50 percent occurred in the South Atlantic Anomaly, whereas only 5 percent of orbital time was spent there.

caused by the action of ionized particles. Most flight components had been tested beforehand, but a few (including the one that experienced problems) had been overlooked. The flight software had to be revised to correct for these events.

Similarly, the Hubble Space Telescope experienced bit errors in communications between subsystems when traveling through the Anomaly. Error detection and correction schemes prevented data loss, but the problem was still annoying to ground controllers. As a result, several high-voltage instruments are powered down before the Hubble enters the South Atlantic Anomaly, an event that happens several times a day.

Numerous other missions have been affected as well. ROSAT, the Roentgen Satellite, was an X-ray observatory that flew for much of the 1990s. The unit's position-sensitive proportional counters

had to be turned off during passage through the South Atlantic Anomaly to prevent severe damage. ROSAT's high-resolution imager could be left on, but could collect no useful data while in the region. The Topex satellite, which flies at an altitude of about 1000 kilometers, is still prone to random upsets in its altimeter as it passes through the Anomaly, preventing proper data collection.

Perhaps the most serious case was NASA's Modis satellite, which was rendered inoperative in 2001 as it passed through the South Atlantic Anomaly. The failure seemed to be caused by an over-voltage shutdown, probably started when a high-energy ion struck a vulnerable metal-oxide semiconductor field-effect transistor (MOSFET), causing it to fail. It took 16 days to get the satellite back on line.

Random glitches affect humans as well. Since the days of Apollo 11, astronauts in

space have reported seeing random flashes of light—with their eyes closed. These flashes are believed to be caused by energetic particles striking sensitive areas of the retina. In a recent experiment, astronauts aboard the Mir wore detector helmets to help researchers correlate the number of reported flashes with the measured particle flux. If the flashes increased when Mir entered the South Atlantic Anomaly, then protons would be revealed as the likely cause; if not, then heavy ions (which appear in equal amounts inside and outside the proton belt) would be indicated. The frequency of the flashes increased in the Anomaly, but only slightly, suggesting that protons alone are not responsible, but neither are heavy ions.

So it seems that the South Atlantic Anomaly may well have a few more surprises in store. 🌐

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