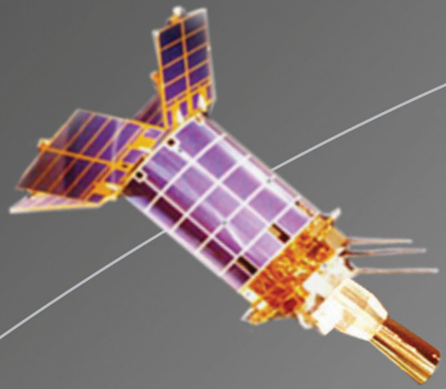


Eyes in Space

Sensors for treaty verification and basic research

William C. Priedhorsky and contributors

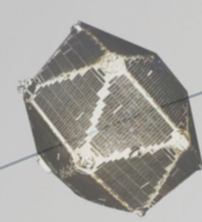
Space-based nuclear threat reduction began with the signing of the Limited Test Ban Treaty (LTBT) in 1963. The treaty prohibited nuclear tests in the atmosphere, outer space, and under water, and was a significant first step toward both slowing the nuclear arms race and curbing the environmental contamination associated with aboveground tests. But in the tense atmosphere of the Cold War, neither the United States nor the Soviet Union would trust that the other had complied with the treaty without a foolproof method of verification.

That method turned out to rely heavily on earth-orbiting satellites, each of which carried a bevy of sensors that would monitor the skies and unambiguously detect aboveground nuclear detonations. The Defense Advanced Research Projects Agency and TRW, Inc., were tasked with designing, building, and fielding these satellites called Vela for the Spanish word "velar," meaning to watch. Los Alamos and Sandia National Laboratories were entrusted with providing the all-important sensors.

Los Alamos was a natural choice to supply these sensitive "eyes" in space. Since the late 1950s, researchers at Los Alamos had used sounding rockets to hoist neutron, gamma-ray, and other detectors into the upper atmosphere in order to gather data from high-altitude nuclear tests. Those same instruments would be adapted for the orbital environment and the nuclear detonation (NUDET) detection mission. But numerous technical difficulties surrounded this new mission, as the sensors would be subject to a host of natural backgrounds and obfuscating signals. Would something as common as a lightning flash be confused with a nuclear event, or would something as exotic as gamma rays from a supernova[1] trigger the system?

[1]This latter question was originally posed by Stirling Colgate, now a senior fellow at Los Alamos, in a 1959 test ban summit meeting. Colgate perceptively recognized the connection between mission and basic research.

Similar to what is being done today to carry out the Laboratory's missions, the scientists then applied their expertise to building a detection system that would behave as planned. They also initiated new research programs specifically designed to further an understanding of background sources and create sensors that could better discriminate nuclear explosions from natural signals. Furthermore, they realized from the onset that a system that was sensitive to, say, lightning could be used to study lightning. Soon, scientists were using NUDET sensors to conduct world-class research in atmospheric science, space-plasma science, and even astrophysics.



Los Alamos detectors have since journeyed over the poles of the sun, probed two comets, and flown to several planets to gather data for basic research. In turn, these highly visible space missions aid our nation's threat reduction efforts. Consider, for example, the recent discovery of water on Mars, discussed in more detail in the sidebar "Geochemical Studies of the Moon and Planets" on page 166. Scientists announced this find after analyzing the neutrons coming from the Red Planet. Because they are generated by cosmic rays bombarding the Martian surface, the neutrons have a known energy spectrum, which becomes slightly distorted if they collide with water molecules. Those spectral distortions were "seen" by the highly advanced neutron spectrometer on the orbiting Mars Odyssey satellite. While the discovery of water on Mars justly fuels the public's imagination and promotes basic research, it also reminds other nations of the United States' remarkable capabilities in neutron detection, in case any nation needs reminding.

NUDET detection for treaty verification and situational awareness remains a Los Alamos mission. The radiation detection system on the Air Force's Defense Support Program (DSP) satellites and the Global Positioning System (GPS) satellites —the same satellites that give us hand-held navigation—are being used for NUDET detection. The last DSP satellite will be launched in 2003 or 2004, after which the next generation of GPS satellites, and perhaps another system, will carry on the mission.

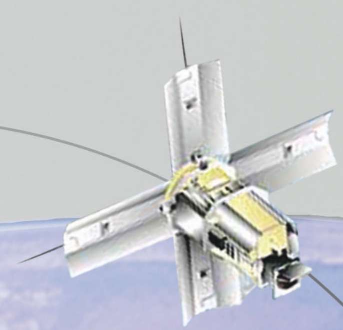
The end of the Cold War, however, changed the world. We needed to assess the capabilities of aspiring nuclear states long before any bomb was detonated and to address problems of nuclear materials control and international terrorism. This broader concept of nuclear threat reduction required new sensing capabilities: new small satellites for space observations, new sensors to monitor effluent streams from factories and power plants, portable sensors for materials trafficking, and sensors that could operate in cyberspace to detect subtle patterns and connections in large masses of data. Like the NUDET systems, these advanced technologies double as research tools and have led to more discoveries of our planet, the solar system, and the cosmos.

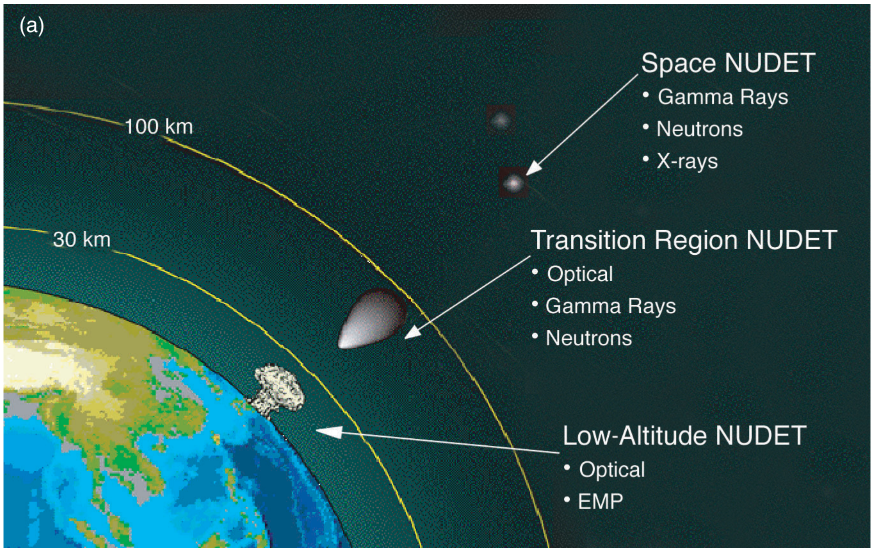
Space-Based Nuclear Event Detection

Remote detection of nuclear explosions is accomplished with sensors that measure the different forms of energy coming from the weapon. Neutrons, gamma rays, and x-rays are emitted promptly within about 2 milliseconds of the detonation. Those radiations then interact with their surroundings to produce secondary radiations, including visible light and electromagnetic pulses (EMPs), in the part of the radio-frequency (rf) band below a few hundred megahertz. Delayed gamma rays and neutrons also come from the nuclear debris. Both the prompt and delayed radiations can be detected by satellite-borne sensors: bhangmeters[2] for detection of optical signals, very high frequency (VHF) radio receivers for measurement of the EMP, plus neutron, gamma-ray, and x-ray detectors.

These sensors studded the surface and filled the insides of the Vela satellites, which were the first used to verify the LTBT. The Velas operated in pairs, with satellites occupying opposite sides of a nearly circular orbit that lay about one-third of the way between the earth and moon. Their sensitive instruments could see the entire surface of the earth, as well as a large region of space surrounding the planet.

[2] The name "bhangmeter" possibly derives from bhang, the Indian name for a type of marijuana. Apparently, some believed that anyone who thought satellite-based optical detection would work must have been smoking something. Equally likely, "b-hang" derives from a two-syllabic way of pronouncing "bang." This pronunciation mirrors the detection of the two distinct optical peaks (one short and one long) characteristic of an atmospheric nuclear explosion.





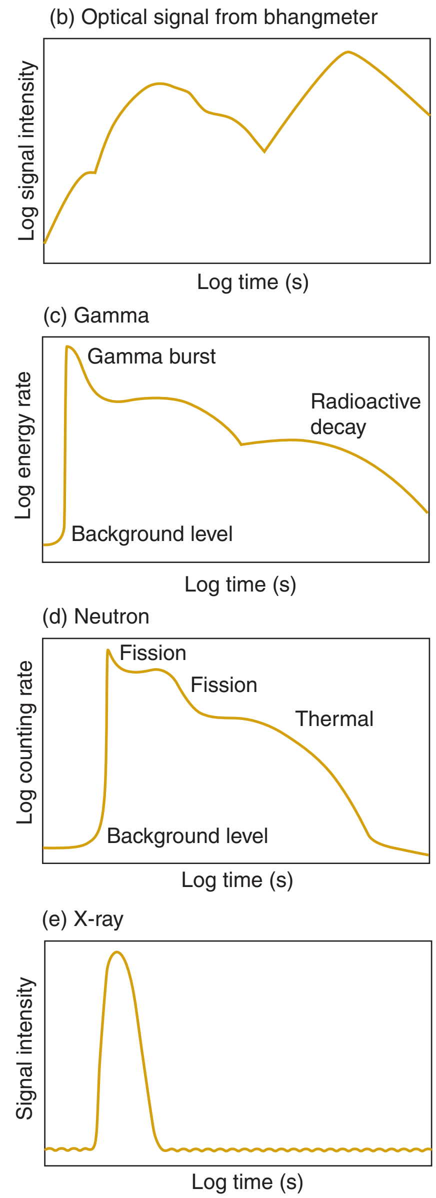


Figure 1. Nuclear Event Detection

(a) No single sensing technology can provide unambiguous detection of a nuclear event under all circumstances, so a NUDET system employs a host of different types of sensors. For events that take place in the troposphere or the lower stratosphere (within about 30 km of the earth's surface), only the optical bhangmeters and VHF sensors yield information because the gamma rays and neutrons are absorbed in this region. The bhangmeter records an unambiguous double-humped optical signal, shown in (b), which is the result of the atmosphere becoming transparent, then opaque, and transparent again as the blast's shock wave travels through it. Unfortunately, clouds can obscure that signal from the satellite's view. The electromagnetic pulse (EMP) is produced primarily when gamma rays "collide" with atoms in the atmosphere, freeing electrons. These become accelerated in the earth's magnetic field and produce a broad spectrum of radio waves. The VHF portion of the spectrum can penetrate clouds and the earth's upper atmosphere and then reach satellite-based sensors. This mechanism for producing the EMP becomes ineffective above 30 km because the atmosphere becomes transparent to the gamma rays. But in this intermediate region, the neutron and gamma-ray sensors become useful. Schematic data from these sensors are shown in (c) and (d). For events in the ionosphere (above 60 or 70 km), NUDET detection is augmented by data from particle detectors and (e) x-ray data.

All told, six pairs of Vela satellites were launched between 1963 and 1969. The initial pair (Vela 1 and 2) carried only x-ray, neutron, and gamma-ray detectors. These would see any events that occurred high in the atmosphere (above about 30 kilometers) and also in space (see Figure 1). Even a detonation on the far side of the moon would be detected because the nuclear blast would expel a gamma-ray-emitting cloud of debris that would quickly be seen.

These first detectors were used as much for system shakedown as for treaty verification. Far from being empty, the space between the sun and the earth is filled with charged particles that boil from the sun's surface and stream through the solar system at supersonic speeds (the solar wind). Interactions between the solar wind and the earth's magnetic field create a tenuous and highly variable plasma, known as the magnetosphere, which surrounds the earth. The Velas' orbit would carry them through the magnetosphere, but in 1963, little was known about that plasma region or about the effects of that region on sensitive instruments. (The Velas were also subject to hostile cosmic radiation, which comes from outside the solar system. Thus, many skeptics gave the instruments no more than two weeks to live. But most instruments lasted well beyond their design lifetime of six months; some, for as long as a decade.)

Adopting a bootstrap approach, scientists used the data from the first Vela satellites to design new types of sensors that would monitor the plasma background and track particle fluxes that could cause false signals in the other detectors. These plasma and energetic-particle sensors, plus bhangmeters and VHF sensors that could identify explosions that took place in the lower atmosphere (refer to Figure 1), were fielded along with the other detectors on the Vela 3 through 6 satellites. The last three pairs of satellites (officially known as Advanced Velas) carried improved NUDET systems, plus sensors that monitored solar activity, terrestrial lightning, and celestial x-rays and gamma rays.

As a series, the Velas worked superbly and were widely considered to have seen every aboveground nuclear explosion that was within their field of view. They established the benchmark for surveillance capability, but their legacy was also one of scientific discoveries. As discussed later in this article, much of our early data on the solar wind was obtained by the Velas' particle detectors, whereas their gamma-ray detectors were the first to observe cosmic gamma-ray bursts, an entirely unknown phenomenon that opened a new doorway into the observable universe.

Starting in the 1970s, the Air Force DSP satellites began carrying NUDET systems, which were continually upgraded for sensitivity, dynamic range, and background rejection. But the basic instruments remained the same as those on Vela, even though extending system capabilities into the extreme ultraviolet (soft x-ray) and rf bands had always been a goal. By the late 1980s, we had concepts for new sensors to operate in those extended frequency bands.

Unfortunately, these new devices presented us with a problem. While we could verify their operation in the laboratory, in space they would be subject to large and poorly understood backgrounds. We needed to test them

The Little Satellite That Could

Diane Roussel-Dupré

The two years 1985 and 1986 were bad ones for the U.S. space program. Three major launches failed, and on January 28, 1986, the space shuttle Challenger exploded in full view of the entire world. These calamitous failures stopped all U.S. space launches for more than a year and left the space community cautious and conservative.

Figure A. ALEXIS
The ALEXIS satellite demonstrated new technologies for treaty verification while carrying out basic research in astrophysics and atmospheric science.

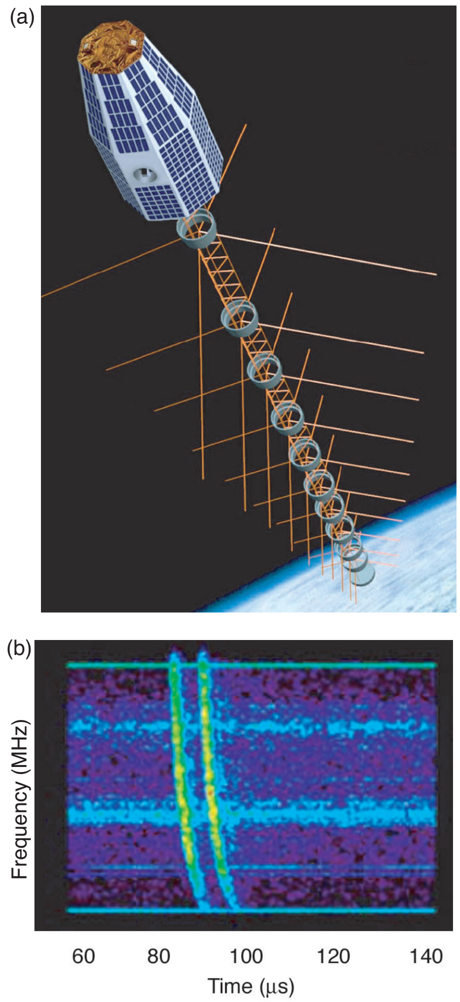
Quixotically, it was during this guarded period that our young experimental team at Los Alamos chose to field the Laboratory's first satellite. The ALEXIS satellite was designed to test new soft x-ray and radio-frequency nuclear detonation (NUDET) detectors. It was funded by the Department of Energy and launched by the Air Force Space Test Program. The rocket was the new Pegasus launch vehicle, which had mixed success on its first three outings. Its fourth launch on April 25, 1993, however, went well, and our rocket gracefully ferried ALEXIS aloft to an 800-kilometer circular orbit. But the satellite itself ran into complications caused by the launch forces.

The Pegasus rocket was outfitted with a video camera to monitor the rocket performance and reveal whether the nose cone deployed cleanly. To our horror, the video footage that was transmitted back to the California tracking station showed that one of the solar panels on ALEXIS had broken loose at the hinge and was dangling freely. We could not tell from the video whether any other damage had occurred or whether the satellite was dead or alive. The first attempts to contact the satellite yielded nothing but silence, feeding our team's worst fears.

For six frantic weeks, the team listened for a signal every time the satellite passed over our Los Alamos ground station. We took a second ground station to an Air Force facility, trying to "shout" at the satellite with a bigger dish. We took pictures of our satellite from the Air Force optical tracking station on top of Haleakala in Hawaii to learn about its status, and we optimized our contact strategy. Our persistence finally paid off with a brief contact from our Los Alamos station, followed by a longer contact and an understanding of the satellite's problems. We formulated a recovery plan, and ALEXIS revived as expected.

ALEXIS was planned as a high-risk, one-year mission. However, as ALEXIS approaches its 10th birthday, it is still fully operational, operated by an automatic ground station in the Physics Building at Los Alamos. The solar panels are losing the ability to provide charge to the batteries, the commercial nickel-cadmium batteries have some trouble charging, and protons from recent solar storms have damaged parts of its memory, but ALEXIS is still "the little satellite that could."

Figure 2. The FORTÉ Satellite and a View of Lightning
(a) The sketch shows an artist's conception of FORTÉ in orbit. The radio antenna, which is pointed toward the earth, is deployed to 11 m in length from a storage container the size of an office wastebasket. (b) This plot shows frequency vs time for a particularly strong NBE collected by FORTÉ. The two pulses correspond to the direct pulse from the lightning and an echo reflected from the ground. The spacing of the two pulses can be used to infer the source height. Free electrons in the earth's ionosphere cause the lower-frequency components of the signal to arrive later than the higher-frequency ones. We quantify and remove this effect to deduce when the event would have arrived at the satellite if the ionosphere were absent. If we see the event from four or more satellites, we can use these timings to solve for *x*, *y*, *z*, and *t* and locate the event in three dimensions.



in space, but unproved instruments could not be deployed on a commercial or military satellite—the cost of failure was too high.

Unable to fly these sensors on someone else's satellite, we chose to fly them on our own. We assembled a small, dedicated team to design and build Los Alamos' first satellite and called in Sandia National Laboratories and AeroAstro, Inc., a start-up small satellite company, to help. Named ALEXIS (for array of low-energy x-ray imaging sensors), our satellite was launched in 1993. The first of the "faster, cheaper, better" satellites, its sophisticated design included a novel uplink/downlink protocol, similar to the file transfer protocol used on the Internet, which allowed us to have very simple, inexpensive antennae on the spacecraft and on the ground and to run the satellite almost autonomously. ALEXIS was the first satellite for which the weight and volume of the scientific payload was greater than the nonpayload (batteries, solar panels, structural components, and others) remainder of the spacecraft, and was one of the first to use computer memory instead of a tape recorder for data storage. After a somewhat shaky start—recounted in the box "The Little Satellite That Could" on page 155—it performed beautifully.

ALEXIS carried a set of soft x-ray imaging telescopes and an rf receiver, called Blackbeard, that was intended to help us understand lightning events. Lightning is a common background for our VHF sensors because the intense electrical discharge produces a burst of rf noise that can mimic the nuclear EMP. The flip side is that our VHF/EMP sensors are excellent lightning detectors that can be used for basic research. Blackbeard, for example, enhanced our understanding of how the ionosphere modifies lightning-induced rf pulses that pass through it and, in the course of its operation, discovered TIPPs (for transionospheric pulse pairs), or doublets of brief, transient rf events that form in energetic thunderstorms at 8 to 10 kilometers above the earth's surface.

Other successes soon followed. When compared with ALEXIS, the FORTÉ (for fast on-orbit recording of transient events) satellite, which was launched in 1997 and is still operational, was a step-up in size and sophistication. Its primary mission was to demonstrate new rf detection technologies that were to be at the core of the V-sensor, a new EMP sensor that will fly on the next generation of GPS satellites. Over the years, FORTÉ mapped optical and rf backgrounds, tested detection algorithms, and provided a wealth of data on the physics of lightning and the ionosphere.

One of the first and most basic of FORTÉ's findings was an explanation for the TIPPs observed by Blackbeard. A lightning discharge between clouds in the troposphere (the roughly 20-kilometer-thick atmospheric layer closest to the surface of the earth) produces an rf pulse that reflects from the ground, so that a pair of pulses is detected by the sensor. TIPPs are closely related to another unusual lightning phenomenon, narrow bipolar events (NBEs), which are intense, in-cloud rf events that occur during thunderstorms and last less than about 20 microseconds (see Figure 2). They are the brightest, most common form of lighting seen by our orbiting sensors.

(a) (b)

Figure 3. Imaging with MTI
The MTI is one of the most accurately calibrated thermal imagers ever launched into orbit. It gathers data in 15 frequency bands—from the infrared to the ultraviolet. (a) An optical image taken by MTI of a section of the Lake Ontario shoreline at Rochester, New York, reveals certain types of information, for example, the existence of offshore sandbars. (b) A thermal image of the same area reveals other features. In this false-color image, red represents hot temperatures, whereas blue represents cool ones. We can now see a plume of hot water from a water treatment plant entering the lake. Data from all spectral bands give us valuable information for detecting and characterizing an area or facility.

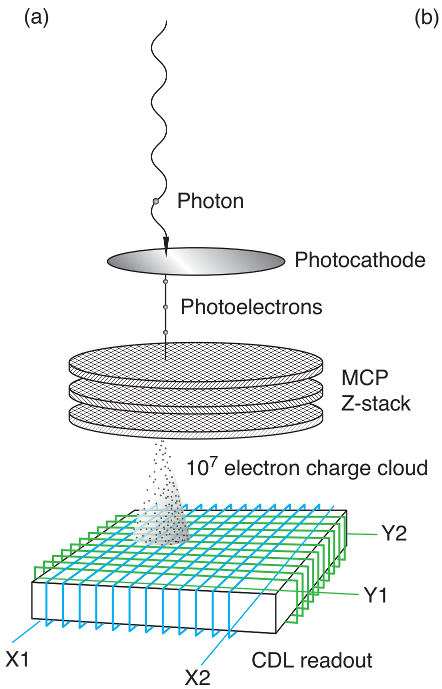
As it turns out, the occurrence rate and source height of NBEs are excellent statistical indicators of the deep convective strength of the parent storm. Deep convection, or convection between the lower and upper troposphere, is the driving mechanism for several forms of severe weather on the earth and is a primary means by which energy—in the form of latent heat—drives the large-scale atmospheric circulation. It is also the primary means by which the atmosphere injects water into the stratosphere, where it profoundly influences the radiative and chemical balance of the atmosphere. Once the new V-sensor is in orbit, we will be able to use its data to map atmospheric deep convective processes in a near-real-time, global manner, particularly over oceanic regions where weather radar coverage is limited. Such maps will be used to support commercial and military aviation.

Advanced Systems. Although we are still advancing the science of nuclear event detection, the alarming rise of nuclear-capable states in the waning years of the twentieth century called for an expanded mission. We needed to develop surveillance systems that could be used for detecting and characterizing facilities that might be producing weapons of mass destruction. But gleaning information about an unknown facility is far more difficult than gleaning the specifics of a nuclear blast. The latter presents a well-defined signature of gammas, neutrons, and electromagnetic radiations, whereas the former oftentimes presents a patchwork of subtle signals that make sense only after detailed analysis. In general, a modern surveillance system will take images at several wavelengths, or spectral bands. Unfortunately, interpreting and piecing together the spectral information is often hindered by uncertainties in the spectral calibration and by an inability to fully compensate for atmospheric effects.

The multispectral thermal imager (MTI), developed jointly by Sandia and Los Alamos National Laboratories and launched in early 2000, was meant to demonstrate advanced imaging and image-processing techniques that could be used in future systems. A major component of the MTI project was absolute calibration of the instrument, which is excellent and the best in its class. MTI takes data in 15 spectral bands, ranging from visible to long-wavelength infrared, which, when combined and analyzed, provide information about surface temperatures, materials, water quality, and vegetation health. Additional spectral bands provide simultaneous information about the atmosphere, such as the amount of water vapor and the aerosol content. All this information helps us construct the profile of a remotely located facility or area of interest (see Figure 3).

Multispectral data are also exceedingly useful for conducting basic earth-science research. The satellite doubles as a national and international resource that provides data to a large number of researchers. For example, MTI was used to study the volcanic eruption of Popocatepetl in Mexico in January 2001 and the effects of the Cerro Grande fire that swept through Los Alamos in May 2000. The MTI team at Los Alamos has built the Data Processing and Analysis Center to distribute data to the national user community.

Los Alamos scientists have also developed ground-based advanced imaging systems. Among them is RULLI (for remote ultralow light imaging), a single-photon detector and imager that can accurately and simultaneously measure the position and absolute arrival time of individual photons coming from a target area. The result is a data set that contains full three-dimensional (3-D) informa-



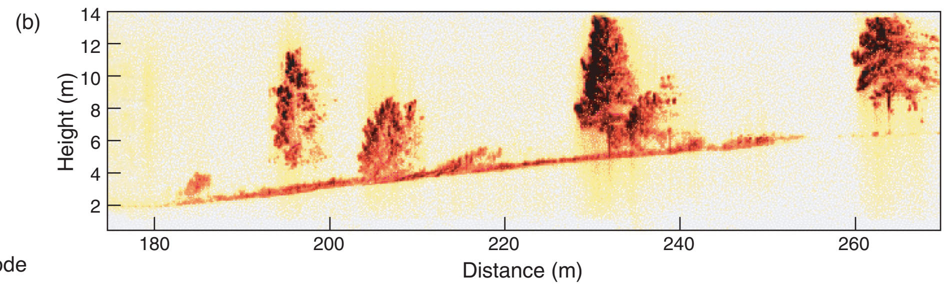


Figure 4. Imaging with Single Photons

(a) The RULLI technology allows us to take 3-D images of subjects that are cloaked in darkness. Individual photons (say from starlight) that reflect off objects are sensed by the RULLI detector and converted into well-defined electrical pulses in the crossed delay lines. Coupled with fast analog electronics and a processor, the sensor system measures the position and time of each photon event. If we use a pulsed laser with known timing characteristics to bounce photons off the subject, we can measure each photon's roundtrip time of flight. We can deduce the distance to the subject with an accuracy of a few centimeters and reconstruct a 3-D image. (b) RULLI's 3-D imaging capabilities allow us to see both the forest and the trees in a Los Alamos canyon. We observed this local scene from a distance of 235 m by illuminating the trees with a 6-mW pulsed laser (about as bright as a laser pointer).The image appears to be a head-on shot, but it is not. The laser and detector were located to the left, looking up the sloping canyon, and the horizontal axis of this picture corresponds to distance. We can reconstruct this view through the trees only because we have full 3-D information.

tion about the area (see Figure 4). Because it can detect activities conducted under the darkness of night, RULLI and its successor technologies can be used for various threat-reduction applications, including airborne, large-area surveillance for perimeter protection.

From Outer Space to Cyberspace

The body of data returned by advanced systems such as MTI, RULLI, or other signal collection and imaging systems is huge. Human analysts face the nearly impossible task of keeping up with this deluge. Increasingly, we must turn to computer-based image-processing tools to automate and assist in the analysis. But a computer's ability to analyze image data pales in comparison with the remarkable human brain. Hence, we developed GENIE (for genetic image exploitation), a new software tool that allows translating human knowledge into an algorithm that can recognize objects and patterns in data streams.

At its core, GENIE is a computer program that develops other computer programs (algorithms). It does so by using genetic programming techniques, which are methods for automatically creating a working computer program by combining, mutating, or rearranging low-level, nonspecific computer functions or programs. As its name implies, genetic programming draws its inspiration from biology, where new species emerge through the exchange and modification of chromosomes.

Training GENIE to find selected features in a data set is an iterative, evolutionary process. Starting with a small data set, or even a single image, an analyst marks features of interest—for example, all regions of water. Given this goal and a substantial library of low-level image-processing functions (for example, edge detectors or spectral filters), GENIE uses genetic programming techniques to produce hundreds of algorithms, each of which finds (to some degree), the regions of water in the training set. The program ranks the algorithms according to a set of "best-fit" criteria.

Although the top-ranked algorithms may work very well, typically they do not find all the features of interest. The analyst then goes through the training set again, retagging missed features or flagging incorrect ones, and GENIE reworks the top-ranked algorithms. After a few such iterations, GENIE "evolves" an algorithm that is optimized to find the features of interest (see Figure 5). The analyst can retrieve the optimized algorithm in human-readable code, automate it, and use it to chew through large, complex data sets.

GENIE is a general-purpose tool for feature classification. Aside from threat reduction, it has been used successfully in detecting cancers and pathogens in humans, looking for topographic features and minerals on Mars, and mapping ash and debris from the World Trade Center after the New York City terrorist attack.

Whereas GENIE enables us to create optimized software, meeting the demands of our expanding threat-reduction mission means optimizing hardware as well. We need to couple a sensor directly to a processor and have the system shoulder much of the real-time data analysis. Unfortunately, in trying to build such a system, we quickly run into size and power restrictions. A general-purpose processing board wastes valuable processing power and real estate because it provides capabilities that are extraneous to our purposes. Our data problems are so supersized that we need every hardware gate to be dedicated to solving our task. Field-programmable gate arrays (FPGAs) deliver this capability.

The FPGA consists of cells that implement logical gate functions, such as NAND, NOR, or XOR. Each cell can be configured to perform different logic functions at different times. A programmable matrix connects the cells to each other, and those connections can be altered by signals sent to the FPGA board. Thus, a user can create different logic circuits (nodes). Similarly, the nodes can be linked together to perform all the steps that are needed for the data analysis (see Figure 6). Furthermore, the nodes process large data sets in parallel, greatly reducing analysis time. Once the task is completed, or the search criteria change, the user can reconfigure the FPGA to perform another task.

By adding memory and input/output devices to the FPGAs, we build, in fact, a reconfigurable computer (RCC). One system we have built for an RCC—we called it POOKA—combines genetic programming with reconfigurable hardware and allows us to build a truly optimized analysis algorithm. How much speed can POOKA bring to feature classification tools such as GENIE? A lot! With a

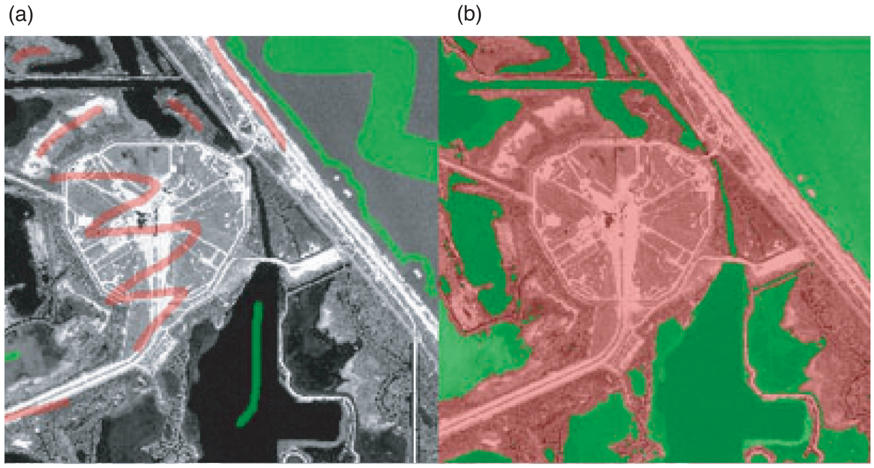


Figure 5. GENIE
GENIE is a computer program that develops pattern recognition algorithms from a limited body of analyst-supplied training data. (a) For a water-finding task, an analyst tags pixels of interest (water) in green and undesired pixels (anything but water) in red. GENIE used this initial information to evolve the mask shown in (b), which includes all the water and nonwater in the image. The user is able to influence the evolution of algorithms by providing additional information and by interactively providing additional training data.

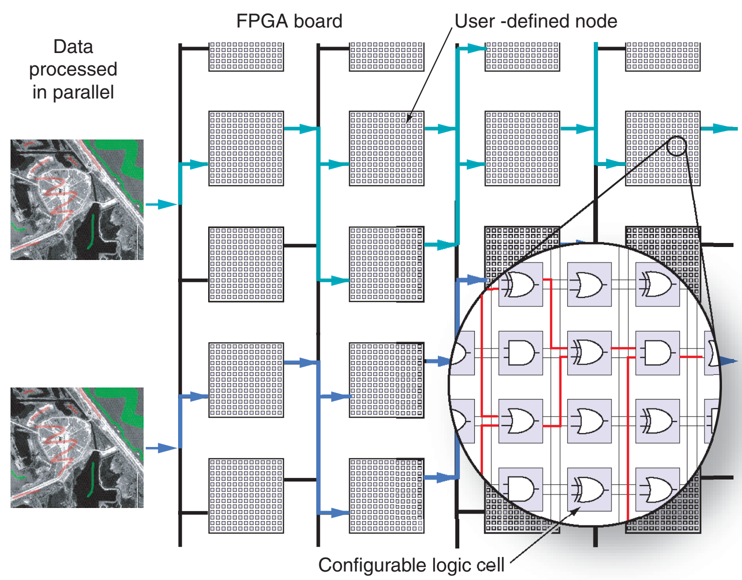


Figure 6. Reconfigurable Computing
The heart of an RCC is the field-programmable gate array (FPGA) circuit board, whose function can be modified by software. The FPGA consists of millions of system gates, which are the basis for the reconfigurable cells. Each cell can be reconfigured to perform a different low-level logic function, such as AND or OR. Many cells are grouped together into a node that performs a complex function, such as edge detection or spectral filtering. A genetic algorithm reconfigures the collection of nodes to create an optimized analysis algorithm. The advantage of the RCC is that many subtasks can be done in parallel. Information is also pipelined so that new data can start to be analyzed even as old data move through the system. The RCC allows us to do complex analysis tasks much faster and with far less hardware than was previously possible.

small data set, new algorithms can be obtained 100 times faster on POOKA than on a conventional computer. Once the system is trained, the optimized algorithm applied to a new data set runs 20 times faster. POOKA is so fast that we are able to search in real time for features in video data streams, for example, from a surveillance camera on an unmanned aerial vehicle. Thus, we can train the algorithm to recognize not just spatial or spectral features but also features that vary between video frames.

The ability to couple a processor to a sensor and optimize the processor to perform specific tasks has allowed us to do multispectral analysis in real time. This achievement has revolutionized our surveillance capabilities and has also opened up amazing opportunities for basic research. (See the box "Gotcha! You Blinked!" on the opposite page 161.)

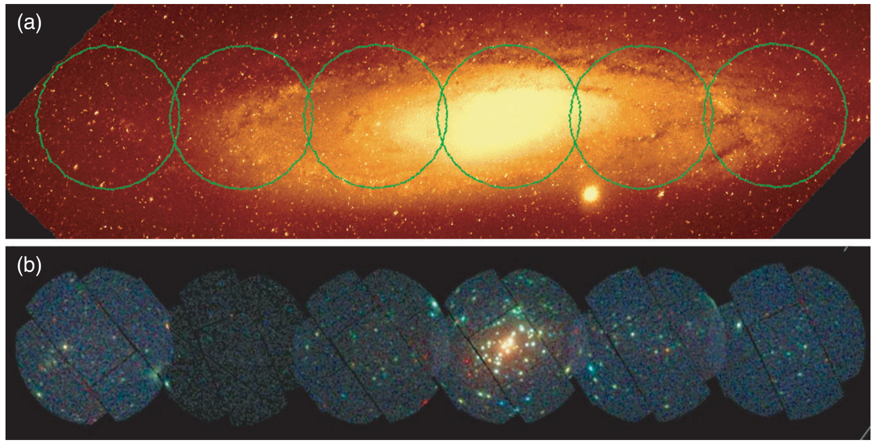


Figure 7. X-Ray Map of M31, the Milky Way's Neighbor
The X-Ray Multimirror Mission Observatory allows seeing the Andromeda Galaxy (M31) in (a) optical light and (b) x-rays. Although the early Vela x-ray instruments could not even detect M31, the observatory is so sensitive that it can resolve 600 x-ray sources within that galaxy. Most of these sources are rare double stars that contain a neutron star or black hole.

Fundamental Space Science and Astrophysics

In 1973, a Los Alamos team announced that the gamma-ray detectors aboard the fifth and sixth pairs of Vela satellites had detected 16 very intense "bursts" of celestial gamma rays, each lasting about a minute but consisting of a number of quick, sharp pulses. The astounding feature of the bursts was their unbelievable brightness—often brighter than the rest of the gamma-ray universe combined! The discovery of bursts immediately raised two scientific questions: What astrophysical sources could emit such rapid, potent spikes of energy, and where were those sources located? Because the intensity of light falls off inversely as the square of the distance, the questions were related. Cosmic sources located millions, or even billions, of light-years away would have to emit orders of magnitude more energy compared with a source located within or near our galaxy.

Theoreticians and experimentalists at Los Alamos were extremely active in trying to shed light on the phenomenon. Collaborating with other institutions, Los Alamos researchers fielded increasingly sensitive gamma-ray detectors aboard the Pioneer Venus Orbiter (launched in 1978), the third International Sun-Earth Explorer spacecraft (ISEE-3, also launched in 1978), and the Ginga spacecraft, which was launched in 1987. But because of their small size, those instruments were insensitive to all but the largest bursts. In addition, the instruments had limited spatial resolution, so data had to be combined with that from other spacecraft to allow accurately locating the burst in the sky. Unfortunately, the initial data analysis often took weeks to complete, far too long to permit follow-up studies by higher-resolution x-ray and optical telescopes. For many years, those deficiencies limited the amount of information available to the gamma-ray burst community.

Things began to change in 1991, after NASA launched the Compton Gamma-Ray Observatory. The satellite viewed the entire sky with an array of relatively large detectors and recorded hundreds of gamma-ray bursts. The data clearly showed that bursts came from all parts of the sky, without any preference for the plane of the Milky Way or for regions around the Andromeda Galaxy. The likely explanation was that sources were uniformly distributed throughout the universe. That view was solidified by the Italian-built BeppoSax satellite, launched in 1996. Data from the satellite could be analyzed fast enough (within 5 to 8 hours) that ground personnel could direct onboard x-ray instruments to observe the source. BeppoSax was the first to detect an x-ray "afterglow" following a gamma-ray burst. The x-ray data allowed researchers to extract redshifts and hence deduce a distance scale. Most physicists now agree that the bursts come from sources located billions of light-years away.

Scientists are still searching for a complete picture of how bursts are produced and are relying on data from the latest generation of spacecraft. The HETE-2 (for High-Energy Transient Explorer) satellite, for example, launched in 2000 with Los Alamos instrumentation and software, processes burst data within tens of seconds. A fast trigger on the gamma-ray detectors quickly relays to observers worldwide event information, which elicits fast responses from ground-based robotic telescopes (such as the RAPTOR system discussed in the box "Gotcha! You Blinked!"on this page). Spectral information can be gathered during the crucial first minutes of the event, while the burst is still happening. In December 2003, NASA will launch the Swift satellite. With its enormous burst alert telescope and Los Alamos triggering and imaging software, Swift will have an even greater opportunity to locate and observe hundreds of bursts per year.

Gamma-ray bursts are but one area of fundamental space research that was advanced by Los Alamos instruments. Another is in the field of x-ray astronomy. This work started with a simple x-ray telescope that flew on the Vela satellite. Although modest in size and limited in performance, that telescope proved to be exceedingly useful because it operated for more than 10 years. It allowed us to do long-term studies of x-ray binaries (peculiar double stars containing a black hole or neutron star) and active galactic nuclei (supermassive black holes at the center of galaxies). That telescope was the forebear of the optical-ultraviolet monitor telescope that we helped develop for the giant X-Ray Multimirror Mission Observatory, a satellite launched by the European Space Agency in 1999. The observatory has studied the x-ray source population in the Andromeda Galaxy, the Milky Way's nearest large neighbor (see Figure 7).

Closer to home, research on the near-space environment has been

Gotcha! You Blinked!

W. Thomas Vestrand

We take for granted that the stars in the night sky are stable from night to night and year to year. But also populating the heavens are short-lived optical transients such as the bright optical flash of January 23, 1999, that lasted about 90 seconds and reached an apparent magnitude in brightness of 9. Estimated to have originated at a distance of 10 billion light-years, it was the most luminous optical object ever measured by humankind. Unfortunately, witnessing similar events is frustratingly difficult. The flashes are generally not preceded by other events and are often over by the time we can train a telescope to the right spot.

The solution is to adapt technology that is used to fulfill our threat reduction mission and couple optical sensors to real-time processors. This procedure has allowed us to develop the first of a new generation of "smart" telescopes that can locate, in real time, celestial optical transients that come and go in less than a minute.

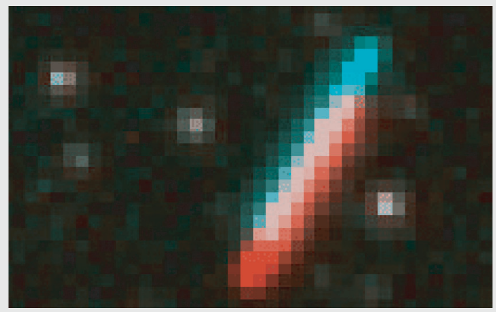


Figure A. RAPTOR
This double image of an asteroid approaching the earth was taken by RAPTOR. Two telescopes, 38 km apart, took each image (shown in red and blue, respectively). Unlike the distant stars, the asteroid position shifts from one telescope to the other.

Our sky-monitoring system, RAPTOR (for rapid telescopes for optical response), is best understood as an analogue of human vision. The human eye has a wide-field, low-resolution imager (rod cells of the retina), as well as a narrow-field, high-resolution imager (cone cells of the fovea). Both eyes send image information to a powerful real-time processor, the brain, running "software" for the detection of interesting targets. When a target is identified, both eyes are rapidly turned to place the target on the central fovea imager for detailed "follow-up" observations with color vision and higher spatial resolution. Because we have two eyes viewing the same scene, we can eliminate such image faults as "floaters" and extract distance information about objects in the scene. Similarly, RAPTOR employs two primary telescope arrays that are separated by a distance of 38 kilometers to provide stereoscopic imaging (see Figure A). Each telescope array has a wide-field imager and a central, narrow-field fovea imager. Both arrays are coupled to a real-time data analysis system that can identify transients in seconds. Instructions are then relayed to point the high-resolution fovea telescopes at the transient.

The RAPTOR sky-monitoring system, which collected its first data in the summer of 2002, will give astronomers the first unbiased global look at the variability of the night sky on timescales as short as a fraction of a minute. It has already imaged an asteroid approaching the earth (see the figure), which stands out from the stars in its field because of the parallax (position shift) between the images taken by the two telescopes.

Near Space and ENA Imaging

John T. Gosling and Geoffrey D. Reeves

Far from being empty, the near-space environment is filled with magnetic fields and solar wind (see Figure A). The latter is a magnetized plasma consisting primarily of protons and electrons that flee the sun's surface at supersonic speeds. As an ionized gas, the bulk of the solar wind cannot penetrate directly into the earth's magnetosphere and, therefore, must be diverted around it. Because the solar-wind flow is supersonic, a bow shock stands off upstream of the earth to cause the solar wind to divert around the magnetosphere.

As a result of its interaction with the solar wind, the day side of the earth's magnetosphere is compressed. Some of those field lines, through the process of magnetic recombination, become interconnected with the magnetic field carried by the solar wind and are carried far past the earth. The result is a long geomagnetic tail on the earth's dark side. Far downstream, the magnetic interconnection with the solar wind is broken, and field lines can return to the earth. This enclosed area within the geomagnetic tail is called the plasma sheet, and it holds a relatively high density of captured and heated solar-wind plasma. During geomagnetic disturbances, this heated solar-wind plasma, along with plasma of ionospheric origin that also resides in the geomagnetic tail, is further energized and accelerated toward the earth, where it collides with and excites particles in the upper atmosphere. The excited particles then emit light that we see as auroras.

Los Alamos pioneered an effort to image and map the earth's entire magnetosphere at one time, a feat that will revolutionize our understanding of this plasma environment. We proposed our innovative imaging technique—known as energetic neutral-atom (ENA) imaging—nearly 20 years ago, demonstrated the principle in the 1990s, and have begun to demonstrate its full potential in the last two years. ENA imaging relies on the exchange of an electron between an energetic ion and a cold neutral atom. Neutral atoms in space are extremely rare, and they seldom collide with ions. But when they do, the ion gives up its charge and breaks free from the confines of the planetary or interplanetary magnetic fields. Except for the weak effects of gravity, the neutral atom travels in a straight line and can be imaged by a detector to "take a picture" of the distant plasma.

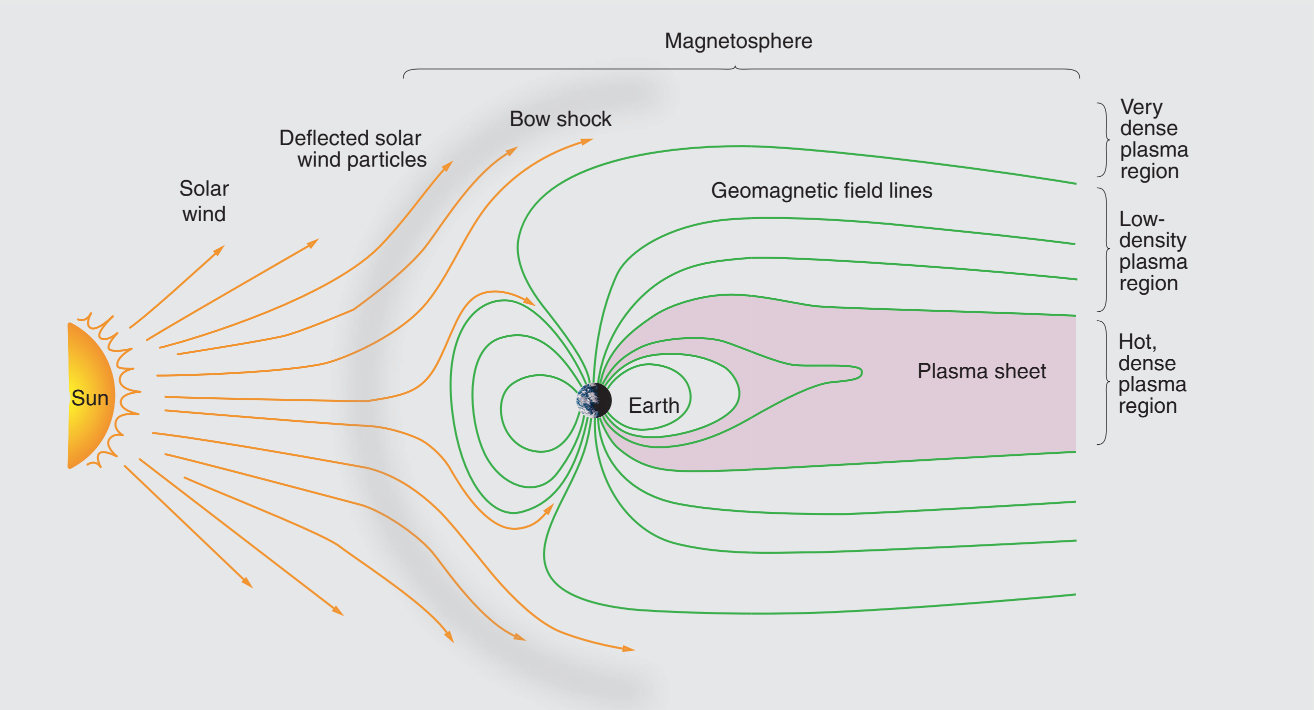


Figure A. Magnetic Fields and Solar Wind in the Near-Space Environment
The solar wind flows at supersonic speed and is deflected around the earth's magnetosphere by a bow shock. The solar wind compresses the day side of the magnetosphere. Field lines from the earth's day side recombine with the magnetic field and form a geomagnetic tail on the earth's dark side. The tail encloses a plasma sheet of hot, high-density solar-wind plasma.

extremely productive and has led to a number of fundamental discoveries about the sun's extended atmosphere, the solar wind, and the interaction of that atmosphere with the earth's magnetic field. Measurements by instruments on the Vela satellites revealed some of the complexity of the earth's magnetosphere and led directly to our discovery of the earth's plasma sheet, a region of concentrated plasma that extends far downstream on the night side of Earth (see the box to the left). Other measurements by Los Alamos instruments on Vela led to the discovery that the sun often impulsively ejects into interplanetary space large amounts of material, which have come to be known as "coronal mass ejections." Los Alamos work in the early 1990s revealed that these ejections, and not solar flares, are the prime cause of major solar-wind disturbances and large geomagnetic storms.

The considerable success of the early Vela measurements prompted NASA to use Los Alamos plasma sensors on a series of satellites launched in the early 1970s. That was the beginning of a long and fruitful collaboration between our two institutions to study the near-space environment, a collaboration that continues to the present. Our instruments have sampled all the different regions of the earth's magnetosphere and have explored the solar wind in considerable detail. Figure 8 shows the solar-wind speed as a function of solar latitude. The data were obtained by Los Alamos instrumentation on the Ulysses spacecraft, a joint endeavor between NASA and the European Space Agency. Ulysses was launched toward Jupiter from the space shuttle Discovery in October 1990. The giant planet's gravitational field deflected the craft out of the ecliptic and into a 5.5-year-long orbit over the poles of the sun. It is the first-ever polar orbit of the sun by a manmade object.

Ulysses is now nearing completion

(a)

(b)

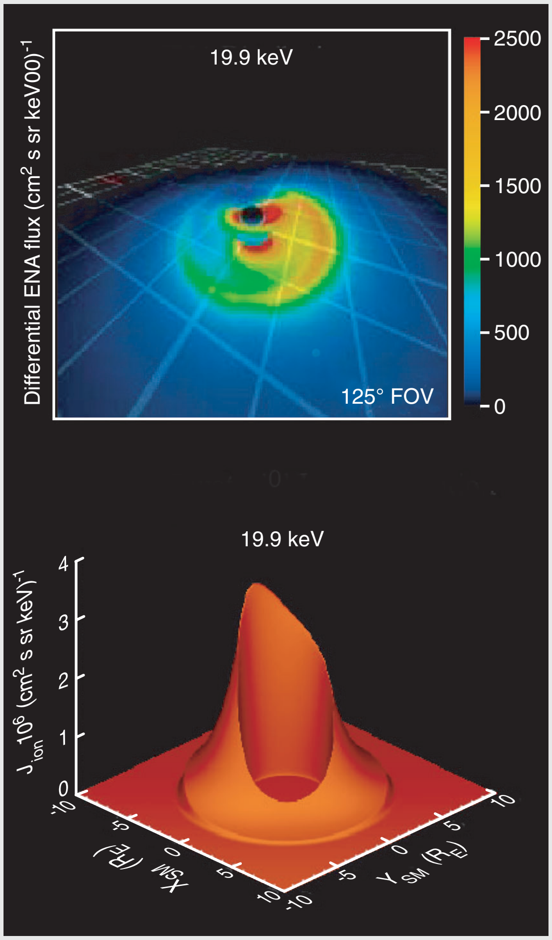


Figure B. ENA Imaging
(a) How would the magnetosphere look if seen from a satellite 53,000 km above the earth? The earth is seen at the center, and the northern polar cap, where ENAs are not produced, is seen as the black, oval shape in the figure. An asymmetric ion ring, the ring current, produces bright emissions around the north and south polar caps as it sweeps around the earth. Ions in the low-altitude "horns" of the magnetic field lines interact with the dense portion of the atmosphere. (b) Viewed from one direction, the ENA emissions are an integral of a 3-D ion distribution convolved with a 3-D atmospheric distribution. A model of the inferred equatorial distribution is shown here.

We produced the first dynamic images of the earth's magnetosphere in the 1990s, using a satellite-based instrument that was originally designed to measure charged particles. In 2000, NASA's IMAGE (for imager for magnetopause-to-aurora global exploration) mission was launched with three types of ENA imagers (for high-, medium-, and low-energy atoms), each fully optimized to image the magnetosphere. Figure B(a) shows what the magnetosphere would look like if you were on a satellite 53,000 kilometers above the earth. Models of the magnetic field and the distribution of atmospheric neutrals can be used with these images to determine the distribution of ions as a function of radius and local time. One such distribution is shown in Figure B(b).

The upcoming TWINS (for two wide-angle imaging neutral-atom spectrometers) mission, which will be launched in 2003 and 2005, will have two medium-energy ENA instruments on separate satellites. The stereoscopic data will allow us to create the first 3-D images of the magnetosphere. The data will also help advance our understanding of "space weather," or the variations in the plasma environment that can adversely affect, among other things, satellite communications and operations, radio and television transmission, the power network, and even the safety of our astronauts in space.

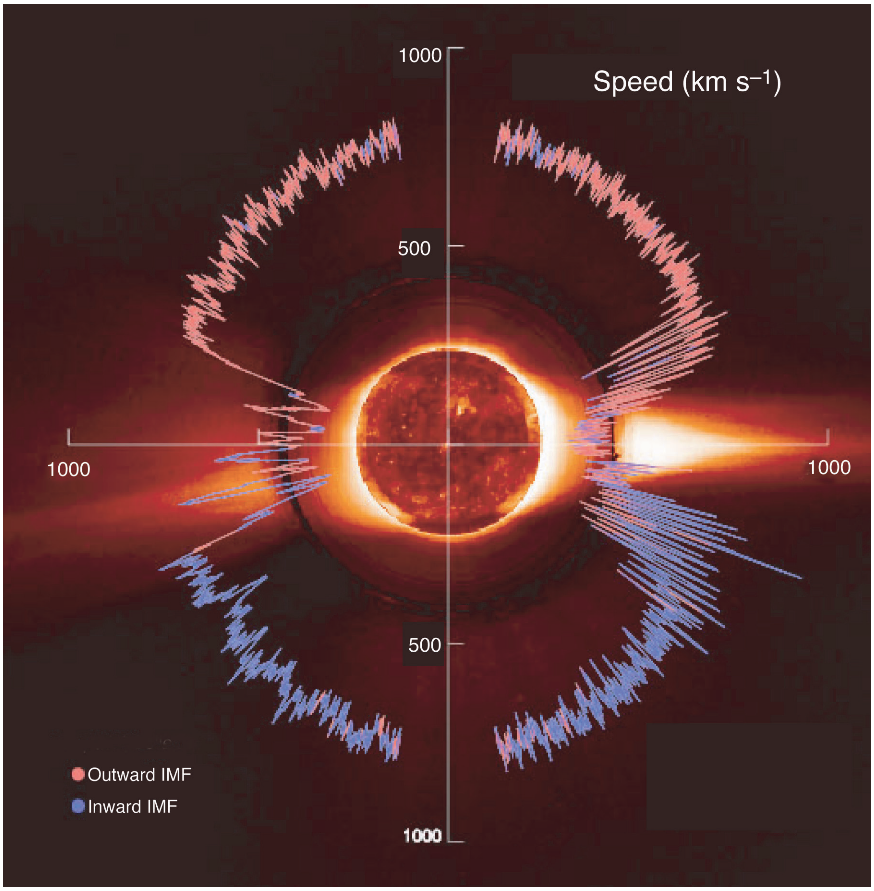


Figure 8. Solar-Wind Speed as a Function of Solar Latitude

A polar plot of the solar-wind speed as a function of solar latitude was measured by Los Alamos plasma detectors on Ulysses. The speed trace is color-coded according to the observed polarity of the interplanetary magnetic field (IMF) that threads the heliosphere. Underlying the speed trace is a set of concentric images of the solar corona, the source of the solar wind, obtained from a combination of space and ground-based telescopes. A striking aspect of the plot is the high and nearly constant speed of the solar wind, outward in the northern hemisphere and inward in the southern hemisphere, observed at high heliographic latitudes throughout the orbit. This high-speed wind originates from relatively dark regions in the solar atmosphere known as coronal holes. Low-speed wind originates in the bright coronal streamers prevalent at low solar latitudes at this phase of the solar cycle. The alternating flows at low latitudes reflect the fact that the solar magnetic dipole had a sizable (20°-to-30°) tilt relative to the solar rotation axis during the interval shown, and as the sun rotated with a periodicity of 25 days, high- and low-speed flows were directed toward Ulysses at regular intervals.

of its second trip over the sun, during which time the 11-year solar-activity cycle rose and peaked. As a pointed reminder of the variability of our local environment, the relatively organized nature of the solar wind measured during the first orbit (refer to Figure 8) was noticeably more complex on this second pass. This change was due to the considerably more complex nature of the sun's magnetic field and corona and the increased number of solar-wind disturbances produced by solar activity at this time.

Near-space research has contributed substantially to a fundamental understanding of, among other things, magnetic reconnection, collisionless-shock formation, and charged-particle acceleration and transport. These phenomena, in turn, have helped us construct models of basic astrophysical plasma processes. Magnetic reconnection, for example, is a restructuring of a plasma's magnetic field, in which field lines oriented in opposite directions break and reconnect to each other with a subsequent release of stored magnetic energy. Magnetic recombination, which has been evoked as the likely power source for the acceleration of charged particles into space during solar activity, is also believed to power the relativistic jets of matter that shoot out from quasars. Although magnetic reconnection cannot be studied directly from a quasar located billions of light-years away, our own near-space environment provides us with a remarkable laboratory to study the phenomenon.

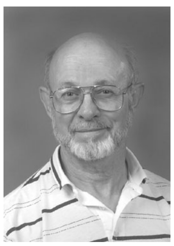
Epilogue

As the Laboratory celebrates 60 years of serving society, it also celebrates 40 years in space. In those 40 years, we have strengthened the national security with sensor and processing systems and used the same capabilities to explore our world from the earth outward to the early universe. With each generation of nuclear detection sensors, we do more with less, driving our systems into progressively smaller but more capable packages, thanks to advances in onboard event detection, device miniaturization, and background processing. The curve of performance shows no sign of turning over. As a result, we are confident of many more discoveries in the decades to come. ■

For more information, please visit http: www.lanl.gov/orgs/nis/ .

William (Bill) Priedhorsky received his bachelor's in physics from Whitman College and his Ph.D. in physics from the California Institute of Technology. After finishing graduate work, he joined Los Alamos National Laboratory, where he has developed sensors for nonproliferation and treaty verification. Bill's current research includes muon radiography and high-energy astrophysics. He is the chief scientist for the Nonproliferation and International Security Division.

Richard Belian, currently a Laboratory consultant (retired from Los Alamos), was a co-investigator on the team that conceived and built the cosmic x-ray detector (XC) flown on the last two pairs of VELA satellites. The XC was the first viable scientific x-ray instrument ever to be flown on a satellite. It made several important discoveries in cosmic x-rays, including the first ever report of a cosmic x-ray burst.



Steven Brumby is co-inventor of the Los Alamos GENIE machine learning/image analysis system, and has been working on a range of space missions to Earth, Mars, and the outer planets. Steven received his Ph.D. in theoretical particle physics in 1997 from the University of Melbourne, Australia, and is a technical staff member in the Space and Remote Sensing Sciences Group.

Edward Fenimore has been a technical staff member at Los Alamos since 1978. At present, he is in the Space and Remote Sensing Sciences Group, where he is working on the high-energy transient experiment (HETE), on the Swift satellites, and on theoretical studies of gamma-ray bursts.

Maya Gokhale is deputy leader of the Space Data Systems Group and project leader of Deployable Adaptive Processing Systems (DAPS), which sponsored the Pixel-Based Multispectral Image Classification (referred to as POOKA) Project.

Jack Gosling is a Laboratory fellow in the Nonproliferation and International Security Division, where he works on various topics in space plasma physics and has authored more than 350 scientific papers.

Cheng Ho is a technical staff member of the Space and Remote Sensing Sciences Group in the Nonproliferation and International Security Division and project leader for the Remote Ultra-Low Light Imaging (RULLI) Single-Photon Sensor Project

Stephen Knox is project leader in the Nonproliferation and International Security Division's Research and Development Program.

David Lawrence is a technical staff member on the Space Physics Team in the Space and Atmospheric Sciences Group at Los Alamos National Laboratory

Geoffrey Reeves is leader of the Space and Atmospheric Science Group in the Nonproliferation and International Security Division. He has spent much time studying the acceleration and transport of energetic particles in the earth's magnetosphere and their effects on space systems.

Diane Roussel-Dupré is manager for the project Cibola Flight Experiment Software Radio Space Demonstration. In the past, she was the flight operations manager for the ALEXIS and the FORTÉ satellites.

David Suszcynsky is a technical staff member and project leader in the Space and Atmospheric Sciences Group of the Nonproliferation and International Security Division.

Tom Vestrand is the project leader for the RAPTOR (rapid telescopes for optical response) and ROTSE (robotic optical transient search experiment) Programs at Los Alamos National Laboratory.

Jay Schecker came to Los Alamos National Laboratory in 1990 as a postdoctoral fellow in nuclear physics. He has been a science writer with *Los Alamos Science* since 1995.