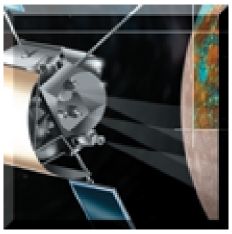

# Advanced Space Instruments

*Robert E. Gold and Robert E. Jenkins*

Instruments are the key components of almost all space missions. They monitor the environment at Earth, observe other planets, and gather intelligence information, providing these data to scientists and analysts on the ground. APL has had a long history of providing innovative space instruments for *in situ* and remote sensing observations for both DoD and NASA. Future missions will require instruments that simultaneously achieve higher performance, smaller size, lower power, and lower cost. Some will require new types of instruments to make measurements that have so far not been made from space. To meet these challenges, APL has been developing several new instruments, including an advanced miniature scientific imager, a miniature energetic ion composition instrument, and a laser ablation mass spectrometer. These instruments employ very large-scale integrated circuits, new packaging techniques, and entirely new means for making some types of measurements. (Keywords: Advanced instrumentation, Advanced technology, Miniaturization, Spaceborne instruments, Spectrometers.)

## THE NEED

Spaceborne instruments can well be described as the raison d'être of U.S. spacecraft. Aside from the current explosion in space communications, which has become a vast commercial enterprise, the government's space program is all about putting instruments in space. These instruments allow us to (1) monitor the Earth, near-Earth, and interplanetary environments, (2) gather precious intelligence on a global scale, and (3) obtain the data to help scientists understand the origins and physical mechanisms controlling the Earth and the solar system. Most of these data are impossible to obtain from Earth-bound instruments. The military intelligence and the scientific knowledge resulting from the data are crucial to social decisions that have a major impact on all life on Earth (see, for example, Ref. 1, which discusses the impact of space remote sensing on environmental policy). In fact, many of these complex social decisions are impossible to make sensibly without the information that can be provided by spaceborne instruments.

The message of these last four sentences is profound. They explain why the space instrument program is one of the most important long-term endeavors ever carried out by humankind. And yet, the average citizen seems unaware of this fact. NASA has to sell its program with words about exploration and space frontiers akin to the opening phrase of *Star Trek*, and DoD publicizes "war-fighting assets." It is hard for the average person to see that simply having accurate and reliable information about what's going on can make or break national security or the protection of our environment. However, the authors, and no doubt the preponderance of the APL staff, sincerely believe this to be the case. As such, the development of space sensors has been a core activity of the Laboratory since the space age began.

The very early APL involvement with space instruments arose during the development of the Navy Navigation Satellite System. At that time, there was a need to understand the effects of the space environment on the radio signals from low-orbiting spacecraft. A space physics group was formed to improve our understanding of the ionosphere, the Earth's magnetic field, and the interactions of both with the solar wind. *In situ* spacecraft measurements were soon recognized as necessary to advance this understanding. The space physics group was the embryo of a long and fruitful APL space physics activity that has expanded into many new scientific areas for both DoD and NASA. The strength of this activity has always been the development of complex space-qualified scientific instruments for *in situ* measurements and for remote sensing of the Earth or other bodies in the solar system.

Some of the instrument types for which APL has long-term experience and recognized world leadership are microwave altimeters to measure surface shape and texture; short-wavelength (visible and ultraviolet) imagers and spectrometers; and particle detectors to measure the composition, flux, and energy spectra of charged and uncharged particles in space. These three areas alone have led to APL involvement in numerous successful spacecraft programs. Some examples of new APL space sensor developments include ultrahigh-resolution mass spectrometers to measure the precise isotopic composition of the material on the surface of bodies in the solar system,[2] extremely tiny and sensitive magnetometers,[3] and instruments to measure the three-dimensional distribution of ozone in the Earth's atmosphere (see Greenwald et al., this issue).

The triad of space physics/geophysics, space instrument development, and spacecraft development is essential for APL to continue to accomplish important missions for the nation's space program. It is the synergy of these three activities that sets apart our ability to contribute to this vital activity. Improvements in the world's space instrument program require improvements in both the spacecraft hosts and the instruments themselves. The tight coupling between the two has unified our advanced technology program.

Over the past 35 years, numerous advanced space instruments have been developed. Despite the tremendous success and capability of the current crop of space sensors, good reasons exist to continue to push the envelope in space instrument technology. There are still difficult, but important, scientific measurements to be made in space for which we have no practical space-qualified instruments (e.g., optically resolving a remote planetary system or measuring the curl of the Earth's magnetic field to determine the magnetospheric currents induced by the solar wind). Also, important science advances can be gained by improving the resolution or the signal-to-noise ratio of existing instruments. Finally, and probably most importantly, lean government space budgets dictate significant improvements in cost, power, and mass just to be able to fly existing sensor capability in the future. The launch and spacecraft cost per kilogram and per watt of instrument payload is extremely high. Pressure abounds to reduce the resource requirements of space sensors so they can be launched by smaller and cheaper boosters and hosted by smaller and simpler spacecraft.

> *The difference between an affordable and scientifically sound mission . . . and* no mission whatsoever . . . *rests almost entirely on improvements engendered by recent advanced instrument development.*

A good example of the problem of spacecraft mass is MESSENGER, a NASA scientific mission recently awarded to APL to carry *seven* instruments to orbit Mercury. A Mercury rendezvous is extremely taxing from the standpoint of orbital energy requirements. Although Mercury is sometimes the closest planet to Earth, a spacecraft must lose most of the Earth's orbital velocity to match Mercury's speed and insert into an orbit around it. The budget caps mandated by congress and NASA for interplanetary missions restrict the possible booster choices to an extent that it is impossible to carry enough fuel to deliver seven instruments of standard weight and power. After hard work and an assessment of trade-offs among launch window, trajectory, power, spacecraft dry weight, and instrument size, a workable baseline design resulted in a mission with 60% of the 1000-kg launch weight devoted to fuel, 37% to the host spacecraft and structure, and 3% to instruments. The authors still chuckle over the seemingly ludicrous value of 33 kg out of the 1000-kg launch weight devoted to the science payload. The seven instruments that typically average 15 kg or more must average about 4 kg to enable the MESSENGER mission. The difference between an affordable and scientifically sound mission to an important target like Mercury and *no mission whatsoever for the foreseeable future* rests almost entirely on improvements engendered by recent advanced instrument development.

Another mission completely enabled by low power and mass is a new type of scientific *in situ* measurement that simultaneously takes samples over a large spatial volume. The kinds of spatially distributed measurements sought by space physicists cover distances of hundreds of kilometers or more and require a swarm or constellation of spacecraft carrying identical instruments. The numbers can vary from a few to perhaps 100 spacecraft. To be affordable, such swarms must be launched in large bunches and comprise very tiny spacecraft, so-called microsats. Such sizes require instruments weighing a fraction of a kilogram and using power on the order of 1 W. The Laboratory has begun working toward such missions and has recently proposed a new NASA mission (Auroral Multiscale) to make spatially extended measurements with four small spacecraft launched together. We also have NASA support to investigate methods for maintaining knowledge and control of the relative positions of many spacecraft in orbiting constellations. Many other problems must be solved to make such missions practical, but the truly enabling technology will be instruments weighing a few tens of grams and dissipating a fraction of a watt of power.

## THRUST AREAS

Let us now examine a selective (owing to space limitations) view of the overall APL program in advanced space instruments. Our efforts have three primary thrusts. First, because spacecraft and instrument mass directly drive the size of the launch vehicle, it is essential to miniaturize space instruments. Savings of a few kilograms can sometimes allow the transition to a smaller launch vehicle, which directly translates into savings of millions of dollars. Often, reduced mass is the key to enabling an entire science mission, as highlighted by the MESSENGER mission. The quality of the science that can be done depends critically on the ability to miniaturize the instruments.

The second thrust focuses on enabling technologies. Some of these technologies may help miniaturize the instruments; others are required to make any instrument that can provide the needed measurements. Examples of these enabling technologies are chip-on-board (COB) construction and application-specific integrated circuits described in an accompanying article by Jenkins, this issue.

The third thrust is the development of entirely new concepts for instruments. These new ideas enable measurements that were not previously possible. For example, one new concept came from the hyperspectral observations of stars setting below the horizon by the Ultraviolet and Visible Imagers and Spectrographic Imagers on the Midcourse Space Experiment spacecraft.[4] APL scientists found that the detailed spectral changes in the starlight as the star set allowed them to deduce the altitude profile of ozone in the upper atmosphere. This has led to the development of a new instrument specifically designed to determine the altitude profile of key greenhouse gases in the upper atmosphere (see the article by Greenwald et al., this issue). NASA is funding development of this instrument for a possible Earth-observing mission.

The emphasis of the remainder of this article is less on technical detail and more on strategy and approach in order to give a clear picture of how our overall advanced technology development fits into a coherent program. (The article by Jenkins, this issue, presents some of the technologies in more detail.) Many of the advanced engineering technologies are interrelated to both spacecraft and instrument efforts. All of the work in advanced electronics and packaging, for example, applies equally well to instruments or spacecraft subsystems.

## ADVANCED INSTRUMENTATION

### Imagers

Imagers are the “workhorses” of space sensors. If scientists had to choose only one sensor that could be put near another body in the solar system, or into low-Earth orbit, it would doubtless be an imager. The old saying, “Seeing is believing,” holds a lot of truth, and there’s nothing like having an extension of your own eyeball right on the scene. A few high-resolution images deliver a wealth of data that detail surface topography and texture, color and intensity variations of reflected sunlight, and atmospheric features and structure. A sequence of such images yields temporal variations in these parameters. Most of us know, for example, that satellite Earth imagery in the visible wavelengths provides enormous information about weather, vegetation, silt, and land use.

In addition to scientific data, imagers in the form of star cameras and other configurations provide spacecraft orientation control from the stars as well as navigation capability from surface features on the body being orbited. Much extra science can be accomplished during a flyby of a planet, moon, comet, or asteroid en route to another target if the onboard instruments can be kept pointed toward that target while flying past. Typical flyby speeds of over tens of kilometers per second cause high rates of change in the line-of-sight direction and require closed-loop pointing control with (you guessed it) a special-purpose imager providing the lock-on and guidance.

The downside to all this versatility is that there are widely varying requirements on the imagers used in these various applications, so much so that essentially a different instrument is generally developed for each.

For example, a star camera needs high sensitivity to see sufficiently dim stars with fast exposure time (to minimize motion effects), a rather large field of view (FOV) that is optimized to deliver unambiguous yet manageable star patterns, and a precise defocus to smoothly blur the star points to achieve subpixel accuracy in star position. A scientific imager to measure, say, the fine structure of surface reflectance at specific wavelengths might need a selectable narrowband filter and a very narrow FOV (about 1°) to maximize resolution.

In addition, the requirements themselves for the various applications are far more stringent than one might imagine. A high-quality scientific imager that must deliver useful data of the kind already described is a far cry from a simple TV camera or even an excellent quality 35-mm Nikon. There are generally requirements on low-temperature operation, stability of focus, resolution, aberration, radiation resistance, and noise immunity that push the limits of technology and translate into cost and mass. Thus, imagers are expensive in terms of mission cost, and it is difficult to fly enough of them on a single spacecraft to satisfy all of our needs and desires. It is essential, for example, to fly redundant copies of onboard imagers for reliability simply because in each application they tend to be mission critical, yet this invariably stresses the cost and mass budgets.

Several years ago, the APL Space Department began an initiative to significantly improve our imager capability. The program had short- and long-term goals. The short-term goals (5 to 10 years) were to reduce the size and mass of an APL-built flight scientific imager by a factor of at least 10, its power dissipation by a factor of 2, and the direct program cost of fabrication and delivery by a factor of 3. The long-term goal was to eventually reduce a scientific-caliber imager down to the few grams and fraction of a watt needed to support spacecraft cluster-type missions.

Instrument size and power reduction has payoff well beyond the huge impact on total mission mass, as described earlier with the MESSENGER example. As size and power decrease, many system issues get simpler and consequently cheaper, e.g., it is easier to find places to mount the instrument, easier to provide thermal isolation, and easier to keep power margins. Thus, achieving even the short-term goals delivers a big return.

In seeking a unifying overall approach to improving our flight imagers, we fell back on what has become a standard APL paradigm, i.e., the biologically inspired architecture. (This approach was first brought into practical terms by Prof. Carver Mead of the California Institute of Technology during the mid 1980s. Since espousing this philosophy as the future direction of integrated circuit development, he has led the world's research into silicon embodiments of the animal peripheral sensing system, and APL has enthusiastically applied the principle to complex systems in general, with varying degrees of success.) Time and again, we have found that clear and sensible approaches to complex engineering problems emerge from the myriad possibilities by applying the analogy of comparable biological systems. (Jenkins discusses this approach for a different technology.)

If we take only a cursory look at the human sensing system, some guidance emerges. First, a large amount of processing is done inside the sensor itself. The processing is specific to the type of sensor (e.g., the inner ear versus the retina), and serves to significantly reduce the bandwidth of the information sent to the next higher level of the nervous system. Furthermore, the adaptability of each sensor (huge dynamic range, large distortionless compression, and regenerative interfaces to the brain) arises in part from a layered type of architecture. In the eye, the first layer of lens, iris, and receptor cells provides an optical system that adapts to light levels, changes focus, and provides a combined wide and narrow FOV by a nonuniform arrangement of rods and cones. The second layer is the retinal cells behind the receptors that provide processing to detect motion, edges, features, etc. The analogy to this layer in the ear is the cochlea. The third layer is the optic nerve that interfaces the retinal processing cells to the cortex. The analogy in the ear is the auditory nerve.

In analogy to the eyeball, we adopted a four-layer architecture (Fig. 1) that we call the Advanced Scientific Imager. The layers—the optics, the detector layer, the processing layer, and the spacecraft interface layer—serve to cleanly partition the system and lead to interesting possibilities. With proper interface design (a nontrivial task), each layer can be optimally developed independently of the others and various design versions could be interchangeable. That is, we could use a new detector electronics layer with a large charge-coupled device (CCD) array to replace an existing smaller version to upgrade image resolution without modifying the other layers. We could swap a narrow FOV optics for a wide FOV optics, reprogram the exposure time (controlled by software), and modify the software data compression algorithm residing in the processing layer to yield two different scientific imagers that use identical electronics. A star camera version might have medium FOV optics and software in the processing layer that analyzes star patterns and computes attitude quaternions.

The results of this layered approach were that, for the first time, significant cost savings were made possible through duplication of parts in a number of imagers performing differing functions on the same spacecraft, and designs could be reused from mission to mission, even as capability was upgraded. The isolation of the spacecraft interface electronics to the bottom

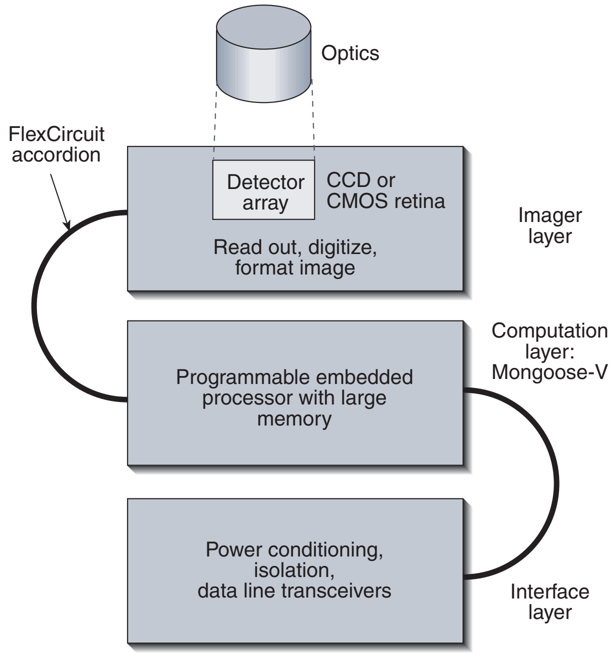

**Figure 1.** The Advanced Scientific Imager is constructed in four conceptual layers, in analogy to the eyeball. The optics layer adapts the imager to the characteristics of the type of scenes to be viewed and focuses the light onto the detector and readout layer. The computation layer extracts the information from the scene, and the interface layer ensures that the information gets to the end-user.

(fourth) layer meant that the adaptation of any version of the imager to a different spacecraft would involve changes to only that layer. (Well, maybe a tiny change to the software too, although we readily admit there may well be no such thing as a small software change.)

This vision of a layered architecture with significant embedded application-specific processing power has provided the unifying structure for much recent work in our imager technology, leading to the achievement of our short-term goals. The image detector electronics layer has been one major focus of the effort in mixed-mode integrated circuit development (see Jenkins, this issue). We have developed a set of three custom chips to handle readout, control, and data buffering for the CCD detector. Implementing the detector interface and control electronics as custom analog/digital VLSI chips in this manner contributes to size reduction, increased reliability, and reduced power. The fabrication of the electronics using COB methods in packaging has led to major size reductions approaching our short-term goals.

To link all the efforts, and to force progress, we implemented a flight version of the Advanced Scientific Imager using all the techniques under development. This version has lightweight scientific-quality narrow FOV optics, a 385 × 550 CCD array in the detector layer with electronic shuttering, image storage capability with no programmable processor in the third layer, and a standard spacecraft serial data interface for the fourth layer. It is roughly equivalent to the imager now on the Near Earth Asteroid Rendezvous (NEAR) spacecraft, without the filter wheel. Using the COB packaging technology, each of the three electronics layers becomes a single 6.4 × 6.4 cm multilayer board. This implementation progressed far enough (through flight boards) to convince us that the technology was viable and to compare the properties of the final sensor to its NEAR counterpart. The story is summarized in Fig. 2. Except for the filter wheel, the comparison shows that our short-term goals on size are realistic. However, the mechanical filter wheel, which provides six selectable narrowband filters that can be rotated in front of the detector array, is a nontrivial contributor to the instrument mass, and is a critical component of scientific imagers to view scenes at different wavelength. Work has begun at the Laboratory to significantly reduce the weight and size of the filter selection mechanism. A promising method now being examined would completely eliminate the mechanical wheel and use liquid-crystal filters whose bandpass properties are voltage controlled.

Other mechanical issues with high-grade imagers are also being addressed. One is the ability to make fine-grained changes in the focal plane while in orbit. Setting the focal plane and maintaining its temperature

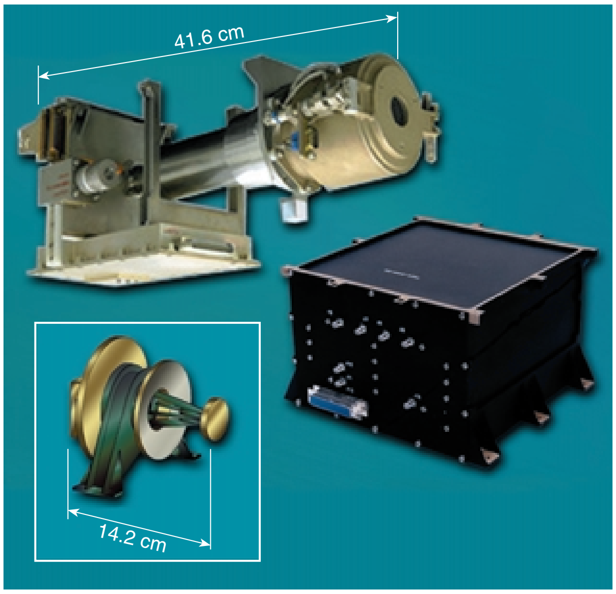

**Figure 2.** The first generation of the APL Advanced Scientific Imager (top) compared with the imager now flying on the NEAR mission. The basic capabilities are identical, except for the lack of a filter wheel on the new version. However, the mass of the new imager is 0.5 kg compared with 7.9 kg (combined weight of sensor, digital processing unit, and harness) for the NEAR imager. The differences are primarily in the advanced integrated circuits, chip-on-board electronics, and compact optics of the new imager.

stability in orbit are chronic problems that must be dealt with during design and fabrication. Furthermore, the focal point is slightly wavelength dependent, so that tiny shifts slightly degrade the image quality as filters are changed. The trick is to perform this delicate adjustment without adding a bulky mechanism. Space Department engineers are investigating the use of "shape memory materials"—new materials that make predictable shape changes with variations in temperature or voltage—for this function.

Work is also under way on a COB version of the processing layer. The electronics for the spacecraft-interface layer are straightforward, but the processor and its resident software represent a major development effort in order to achieve a truly flexible miniature scientific imager. We envision the advanced imager to be completely autonomous in its boot-up and recovery operations, and simply respond to commands and requests from the spacecraft. The embedded processor must be designed with a core operating system that can monitor its own health and automatically reset itself or reboot automatically if necessary.

For all versions of the scientific imager, the software would process commands, control the operation of the detector-layer electronics, and manage the collected image data. Beyond that, as in the animal peripheral sensing system, specialized functions would be performed depending on the specific application. The scientific versions would carry out image compression, and ultimately execute some image analysis to allow event-driven data gathering. The star camera version would process the images for star positions and perform lock-on operations, star pattern recognition, and attitude computations, perhaps running a Kalman filter to continuously estimate angular velocities. An optical navigation application would provide map matching and position computations. And so on.

These computations are nontrivial and require significant computing resources. The processor must be a radiation-hard 32-bit machine with floating-point capability and a processing rating of at least 10 to 20 million instructions per second. It must have 100 or more megabytes of random access memory, and also megabytes of radiation-hardened erasable, programmable read-only memory to hold programs and start-up data so it can automatically reboot without help from the main spacecraft computer. We have selected the available and flight-qualified Mongoose-V radiation-hard processor as the initial version to be integrated into the design, and this work is ongoing. Higher-speed and lower-power space-qualified processors are continually being developed. With proper design, it should be possible to upgrade to a new processor board as easily as replacing any of the three layers in the architecture, provided, of course, that our software is written in a transportable high-level language, and that we encapsulate hardware interfaces and operating system functions properly. Furthermore, the resident software must be designed so that the different functional versions can be kept under configuration control and can be easily swapped. The processing layer with its resident software is the riskiest and largest piece of the overall program, but it is the part that truly makes the versatility vision come to life. We are anxious to begin this final part of the development.

## Spectrometers

### *Miniature Energetic Ion Composition Instrument*

Plasma (ionized gas) is the most common form of matter in the universe. The interactions of ions and electrons in space plasmas with magnetic and electric fields in the atmospheres of stars or the magnetospheres of planets can accelerate the ions to very high energies. Space scientists have been trying to understand the origins of planetary magnetospheres and the solar wind for more than 40 years. They examine the spatial and temporal distribution of energetic ions as well as their atomic and isotopic composition to deduce their origin and details of their acceleration and propagation. These studies have been conducted with a variety of instrument types over the years.

During the past 15 years, instruments that measure both particle energy and speed have shown that they can determine the particle mass with atomic species or sometimes isotopic resolution over a wide range of energies. These instruments, known as time-of-flight (TOF) spectrometers, measure particle speed by the time it takes the particle to fly across the innards of the instrument. A very high resolution TOF spectrometer onboard the Advanced Composition Explorer (ACE) mission is studying the isotopic composition of solar energetic ions. Another TOF instrument on the Cassini mission will examine the atomic composition of energetic particles in Saturn's magnetosphere. These are excellent tools, but TOF instruments have been power hungry (15 to 25 W) and massive (10 to 20 kg).

APL scientists and engineers have designed a miniature TOF spectrometer that is about the size of a hockey puck, yet it has all of the sensitivity of its massive predecessors. The particle flight path in the instrument head is only 5 cm, compared with the 50-cm flight path in the ACE high-resolution spectrometer. To measure 10-keV protons in this instrument, we must accurately measure time intervals of 36 ns, and to measure 1-MeV protons, we must measure a flight time of only 3.6 ns (about the time that light travels 1 m).

Making these very short time interval measurements used to require high-powered electronics. In the TOF instrument, a new type of high-speed integrated circuit is replacing boards of electronics. This chip, developed at APL, measures time intervals with an accuracy of ±50 ps for a few milliwatts of power. The TOF chip, although developed for energetic particle instrumentation, may open up entirely new ways of designing instruments for many different types of measurements. A comparison of the sizes of the Cassini and the miniature TOF instruments is shown in Fig. 3.

### *Laser Ablation Mass Spectrometer*

Another example of space instrumentation is of an entirely new form—a miniature mass spectrometer for use on the surface of comets, asteroids, and planets. Planetary science from space is about to enter the third stage of exploration. The first stage is gross reconnaissance. All of the planets except Pluto have been visited by at least one spacecraft flyby, and spacecraft have flown past four asteroids and one comet. We have seen the gross structure of these bodies. The second stage is orbital missions to examine the structure of planetary bodies and begin the process of understanding their origin and evolution. Venus, Earth, Mars, and Jupiter have already had orbital missions to examine the shape of the surface, the structure, and the coarse composition of these bodies. The APL-built NEAR spacecraft[5] is about to orbit the asteroid 433 Eros for 1 year to examine it closely.

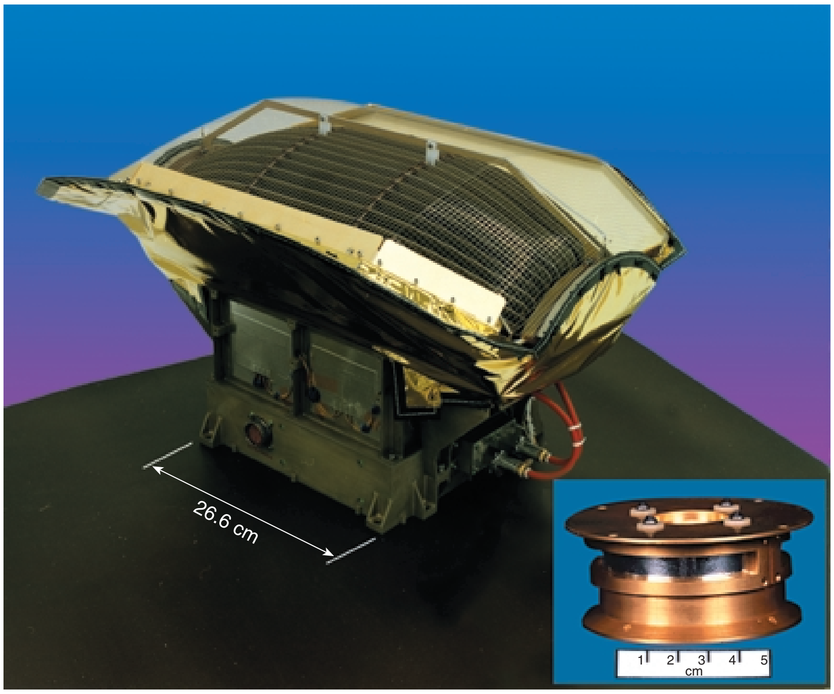

**Figure 3.** A comparison of the time-of-flight (TOF) sensor for the Magnetospheric Imaging Instrument (MIMI) on the Cassini mission and the sensor for the Miniature Ion Composition Instrument (inset). This comparison actually overstates the size difference between the two because the TOF portion of MIMI is only the large rectangular box that forms the lower half of the instrument. The large deflection plates at the top exclude charged particles and only admit energetic neutral atoms.

The third stage of exploration requires landed packages to examine portions of the surface in great detail, e.g., the atomic and isotopic composition of the rocks, soils, and regolith. Atomic analysis can reveal the mineral composition of the rocks, while isotopic analysis contains information about the origin of those materials. For example, the ratio of neon isotopes $^{20}$Ne/$^{22}$Ne in terrestrial rock samples is very different from protosolar grains. These grains are believed to be pristine samples of the original solar nebula and have been unchanged for billions of years. One example of a third-stage exploration mission was the Mars Pathfinder.[6] The Sojourner rover carried an alpha, proton, X-ray (APX) instrument to examine the rock composition. It was able to determine the rough atomic composition of a few rocks on the Martian surface. APX instruments are limited, however, because they only measure elements in the atomic number range from magnesium to iron, and they also have atomic, not isotopic, resolution.

For the last 3 three years, APL has been developing the Laser Ablation Mass Spectrometer[2] (Fig. 4). This instrument fires a very short laser pulse at the surface of a rock to vaporize and ionize a tiny segment. Some of the ions enter a reflectron analyzer[7] where an electric field turns them around and directs them into a detector. The properties of the electric field in the reflectron are designed so that the time from the laser pulse until the ions reach the detector is independent of the energy of the ion and depends only on its mass. The lightest ions (hydrogen) reach the detector first, followed by the heavier ions, all the way to the highest masses for which the instrument is designed (≈1000 amu). Thus, just by watching the time history of ions hitting the detector, the full isotopic composition of the sample is determined. The whole measurement takes only a few tens of microseconds.

Laser ablation mass spectrometry has been used in laboratories for a few years and is regarded as one of the most sensitive tools for microscopic composition analysis. Laser ablation spectrometers are a natural candidate for space instrumentation except that most are very large, not something that could be put onto a Mars Pathfinder–sized lander. The instrument being developed at APL will be

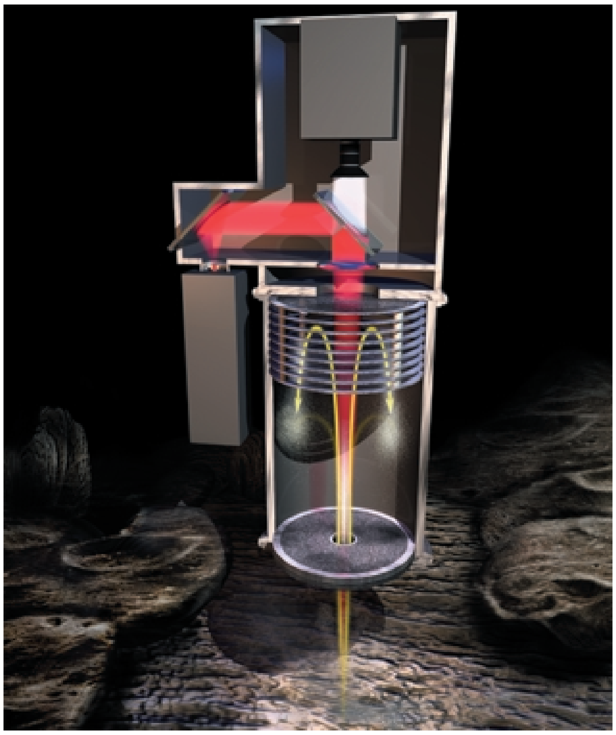

**Figure 4.** The Laser Ablation Mass Spectrometer as it may operate on the surface of an asteroid. The laser focuses a pulse of high-intensity light, shown in red, at a small spot on the rock surface. Some of the ions produced in the fireball enter the instrument and are deflected by the electric field down to the microchannel plate detector (the gray annular disk at the front of the instrument). The camera at the top lets the scientist see which rock grain has been targeted.

about the size of a 1-L bottle and weigh less than 5 kg. Figure 5 shows the isotopic composition of a meteoritic sample measured by the APL mass spectrometer.

This instrument will have another important feature, i.e., a microscopic camera in the optical train to show the exact part of the sample that is being measured. Since the spot being vaporized is less than 0.005 cm in diameter, it can be focused on individual grains in the rock. With this capability, scientists need not work with just the average bulk composition. They can examine the minerals in the rock individually. This is especially important for breccias, rocks assembled from angular fragments broken off parent rocks that have been cemented together into a composite rock.

If the laser power is lowered somewhat, the molecules in the sample can be ionized without breaking them apart. This can be helpful in understanding the exact chemical form of the minerals in rock or soil. It may also allow the instrument to search for organic compounds on the surface of other planets.

## THE FUTURE

As noted earlier, the available instruments will often be the determining components for future space missions. Whether the missions serve the needs of NASA, DoD, or other sponsors, the key to mission success is often advances in instrumentation. APL is currently working on a wide variety of instruments for several ongoing and future missions. Two are preparing for launch on the TIMED and IMAGE missions for NASA. Six others are just in the development stage, two for the CONTOUR mission and four for the MESSENGER Mercury orbiter mission. Several other instruments have been proposed for competitive mission opportunities and are currently awaiting decisions. But it is the advanced technology developments, such as those described herein, that will enable the highly capable and miniature instruments of tomorrow's space missions.

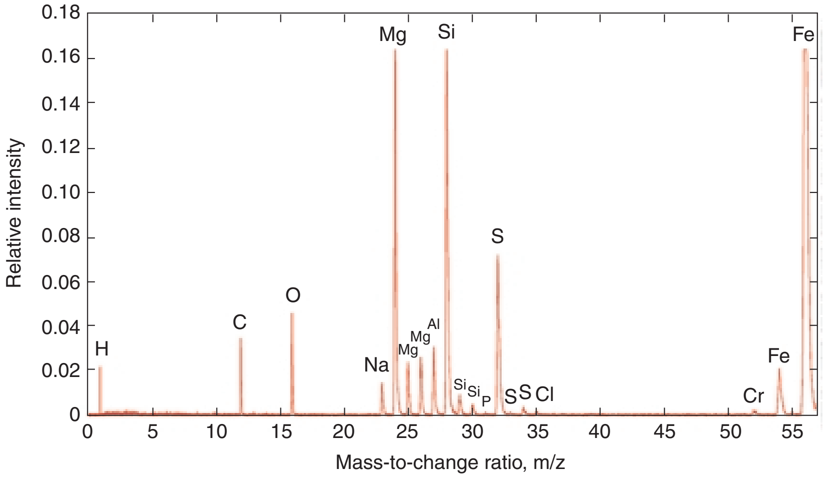

**Figure 5.** An isotopic mass spectrum of a meteorite produced by a laser ablation mass spectrometer. This is the result of a single laser pulse. The entire measurement took less than 100 μs.

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