Laser “Footprints” on Mars
In this issue, we feature two old warhorses of exploration: Galileo launched in 1989 and reached the Jovian system in 1995; Mars Global Surveyor launched in 1996 and entered Mars orbit in 1997. Long after their primary missions ended, both spacecraft are still returning data, testifying to the imagination, ambition, and skill of the human explorers who stand behind them.

Both spacecraft teams confidently overcame mechanical failures threatening their missions. On Galileo, the main antenna refused to open, rendering it useless. Communications had to be routed through a smaller antenna, but thanks to mission engineers, the spacecraft returned spectacular amounts of data.

On Mars Global Surveyor, a small damper failed, causing a solar panel mount to crack during deployment and forcing a delay in the spacecraft’s reaching its mapping orbit. Still, the avalanche of data from the mission buried many old assumptions about Mars, and we now see the Red Planet as a much more vital and dynamic world.

Achieving grand ambitions, overcoming failure, transforming knowledge—these missions have taught us what is possible when we are demonstrably confident, clever, and smart. Planetary exploration is a beacon to humankind of all that we can become.

—Charlene M. Anderson

Features

4 Shedding Light on the Red Planet: Science Findings From the Mars Orbiter Laser Altimeter

Planetary Society Board member Maria Zuber also serves as an investigator on the science team for the Mars Orbiter Laser Altimeter, affectionately known as MOLA, which flew on Mars Global Surveyor. We’ve frequently featured brightly colored MOLA images in these pages, but until now, we’d yet to devote an entire article to the results of this hugely successful experiment. Here, Maria, with David Smith and James Abshire, reports on MOLA’s key discoveries.

10 Oceans, Ice Shells, and Life on Europa

Now that the Galileo spacecraft has all but clinched the debate over whether Jupiter’s moon Europa possesses an underground ocean, argument swirls around whether the overlying ice crust is thick or thin. This may seem like an arcane question, but the answer may further our quest to understand the place of life in our solar system. Crustal thickness determines what sort of energy might be available to any possible Europan life-forms. And it would dictate what sort of robots we build to explore the Europan ocean.

16 Breaking New Ground: Red Rover Goes to Mars

Our Red Rover Goes to Mars contest has shifted into high gear! At the World Space Congress, held this year in Houston, Texas, The Planetary Society and the LEGO Company announced that our education experiment will fly with NASA’s Mars Exploration Rovers, set to launch in 2003. The contest to select Student Astronauts, who will actually participate in mission operations, is now under way. If you are a bright young student between the ages of 13 and 17, or you know someone who is, you’ve got to read this article.
Honoring Voyager

Normally, I finish reading The Planetary Report just before the next issue arrives. The special Voyager issue (September/October 2002) changed all that. Before even checking the other mail I received that day, I had read the magazine cover to cover! Hats off and thumbs up to all the staff in Pasadena.

Kudos, too, to all those who were part of Voyager. Your shoulders are broad and strong. Thank you for the view. It is more beautiful than we could ever have imagined.

—JOE SALVADORE, Frisco, Texas

My copy of the Voyager special issue arrived today. The entire magazine is superb—the best retrospective I’ve seen on Voyager. Many thanks!

—BRAD SMITH, Santa Fe, New Mexico

Editor’s note: Brad Smith led the imaging team on the Voyager project.

Your special issue on Voyager brought back fond memories. The pictures of Voyager’s encounter with Saturn that I first saw as a teenager started my lifelong interest in the solar system. I have followed every Voyager encounter after that, and every planetary probe since.

The shimmering of our view of planets as simply giant balls of gas and their moons as dead rock should forever inspire exploration of our universe. I hope that Galileo and Cassini won’t be the only outer planet probes we have to look forward to. In a world turning increasingly inward as well as fearful, Voyager will always be there to represent hope and to inspire future generations.

—WILLIAM V. STINE, Fairfax, Virginia

In your September/October “From The Editor” column, you posed the question of why the Voyager spacecraft were so much more successful in the public imagination than were the Pioneers. I think the answer is very simple: the enormously better pictures that were returned by the Voyagers. In contrast to the crude images obtained by the Pioneers, the Voyagers supplied us with pictures we might have taken ourselves had we been there.

—PETER H. LLOYD Todttington, United Kingdom

More on “What to Tell Them”

James Walker’s challenge to explain the importance of science and space exploration in twenty-five words or less (see the July/August issue of The Planetary Report) set me thinking, and I realized that the practical implications don’t really matter.

The human spirit exists to experience joy. Essential to that pursuit are curiosity and exploration.

—ROBERT TARRANT, Uxbridge, United Kingdom

I would like to respond to James Walker’s letter by paraphrasing David McCullough: Not knowing the story of this ancient and elegant universe that spawned us isn’t simply stupid. It’s rude.

—CHRIS TODD, Shoreline, Washington

If we ever expect to figure out what we are, we need to know where we are.

—TERRY CHURCHMAN, Altadena, California

Exploration of the unknown and greater understanding of planet Earth, our home, are as nourishing and vital to the human spirit as food and shelter.

—DAVID HUFNAGEL, Golden, Colorado

We may discover that our role in the great scheme of things is perhaps more marginal than we like to imagine.

—SHELAGH BURKE, Clonmel, Ireland

Mistaken Identity

On page 17 of your September/October issue, one of the photo captions reads: “Astronaut James McDivitt is shown here on a space walk from a Gemini orbital flight. His hand is visible . . .”

Indeed, Mr. McDivitt had a hand in this photo, but as the astronaut who took the photograph. The subject of the photograph is Edward H. White II, America’s first space walker.

—CARL ALESSI, Yorba Linda, California

Please send your letters to Members’ Dialogue The Planetary Society 65 North Catalina Avenue Pasadena, CA 91106-2301 or e-mail: tps.des@planetary.org
A planet’s topography tells the story of its evolution, as many geologic processes—including tectonics, volcanism, and erosion—are controlled by elevation or surface slope. To better understand Mars’ rich geologic history, early spacecraft missions used a variety of methods to try to measure the shape of the Red Planet. Viking-era analyses produced models of surface heights on Mars with average errors of about 1 kilometer (0.6 mile), although in some areas, errors were as much as 5 kilometers (3 miles). In addition, early maps failed to determine locations accurately in latitude and longitude. Errors in surface location were typically less than 3 kilometers (2 miles), but some areas were misplaced on maps by more than 15 kilometers (9 miles).

The payload on Mars Global Surveyor (MGS; see the
The Instrument

The MOLA instrument operates by firing infrared laser pulses at Mars, then measuring how long it takes the laser signal to bounce off the planet’s surface (or clouds in some cases) and return to the spacecraft. Knowing the speed of light allows scientists to derive the distance to the Martian surface at the time of the laser pulse. Combined with knowledge of the spacecraft’s location in space, this information makes it possible to determine the planet’s topography (see “Getting Technical,” page 6).

While MOLA’s primary function is to measure surface topography, the instrument supplies two additional measurements. First, it measures the roughness of the surface in laser-pulse-size sections (a laser pulse is about 100 meters in diameter by the time it reaches the surface). A flat surface will return the entire pulse at once, whereas a rough surface will spread out the pulse. MOLA also measures the reflectance of the Martian surface in the near infrared in a passive mode (that is, without use of the laser-ranging function described above).

“Sea Level” on a Planet With No Sea

Topographic models of a planet require a reference point. On Earth, this is typically sea level. But on Mars today, there is no sea.

Pre-MOLA topography on Mars was referenced to an imagined surface where the atmospheric pressure was 6.1 millibars. However, using a pressure surface as a topographic reference introduced large errors into estimates of elevation. That is because the height of any given isobar (constant pressure surface) varies by as much as 2.5 kilometers (1.6 miles) over the Martian year due to the seasonal exchange of carbon dioxide between the atmosphere and polar caps and to the dynamic motions in the atmosphere.

To rectify this problem, the MOLA science team chose a static reference surface. Zero elevation on Mars from MOLA is defined as the gravitational equipotential surface (an imaginary surface with the same gravitational geopotential everywhere across it) whose average value at the equator is equal to the mean radius of the planet. The average height of the 6.1-millibar pressure level occurs at approximately –1,600 meters relative to the zero reference of MOLA topography for the first day of spring in the northern hemisphere.

MOLA data have been used to redefine the geodetic grid of Mars and have provided up to one hundred times better knowledge of the absolute locations of latitude and longitude and one thousand times better knowledge of the planet’s radius over all previous models of Mars. Locations on Mars sampled by MOLA are now known to approximately ±100 meters, and vertical positions are known to approximately 1 meter.

Global Topography

MOLA’s global topographic map of Mars (at the top of this page) has a spatial resolution of 1 kilometer and a
radial accuracy of about 1 meter. The map reveals the major physiographic provinces on Mars, showing the striking difference between the southern and northern hemispheres.

Mars’ hemispheric dichotomy has been known since early maps of the planet, but MOLA data have clarified significant aspects of this puzzling feature. The dichotomy has two components: a contrast in surface geology and an elevation change.

Regions with differing geologic style are separated by what is known as a dichotomy boundary. Mars’ southern highlands are more heavily cratered than the northern lowland plains. The difference results from resurfacing of the northern hemisphere by volcanic flows and sediments.

MOLA’s topographic map also shows that Mars’ south pole is 6 kilometers (4 miles) higher in elevation than the north pole, with a south-to-north slope of 0.036 degree. As we will discuss later, this global longitudinal slope—which predates other geologic features on the surface—means that the northern lowlands represent a sink for water and sediments. Along part of the north-south dichotomy boundary, the elevation increases as much as 3 kilometers (2 miles). The area may represent an erosion boundary providing a source for some of the sediment fill in the northern plains.

The difference in elevation between the north and the south has been attributed either to a large impact or impacts in the northern hemisphere or to intense mantle dynamics. Recent modeling has established the feasibility of the latter origin, and while northern lowlands seem to be inconsistent with the proposed impact origin, evidence for such a process may have been erased by more recent geologic events.

The Red Planet’s other major feature examined by MOLA is the Tharsis province. Centered near the equa-

Getting Technical

The Mars Orbiter Laser Altimeter (MOLA) instrument, which is mounted on the downward-facing deck of the Mars Global Surveyor (MGS) spacecraft, operates by firing infrared laser pulses at Mars and then measuring the round-trip flight time of the laser signal. The laser transmitter consists of a solid-state (chromium- and neodymium-doped yttrium aluminum garnet, aka Cr:Nd:YAG) oscillator excited optically by a 36-bar diode array to produce laser action at 1,064 nanometers (the near infrared). A Q-switch causes the laser to emit approximately 8-nanosecond-long pulses at a rate of 10 Hertz.

MOLA’s receiver is a 0.5-meter-diameter, gold-coated beryllium telescope. The receiver optics includes a narrow [2.0-nanometer-wide] bandpass filter that rejects the solar photons near the laser wavelength and a silicon avalanche photodiode detector. The receiver also contains a time interval unit—a binary counter that records the number of clock cycles to measure the time between transmitted and received pulses. In addition, the instrument contains an 80C86 microprocessor that executes the flight software.

MOLA was designed to range continuously to the surface of Mars during the MGS mapping mission. The backscattered laser pulse is detected within a range gate, that is, a period during which the returned pulse is expected. The telescope collects photons from laser pulses scattered by terrain or clouds, which are then focused on a detector that outputs a voltage proportional to the rate of backscattered photons. When this voltage exceeds the detection threshold, the time interval unit is stopped and the round-trip time of flight recorded.

By interpolating the MGS orbital trajectory determined from radio tracking of the spacecraft to the time of the laser measurement, one can determine the distance between the spacecraft and the center of mass of Mars. Subtraction of the range to the surface from the MGS orbit yields measurements of the radius of Mars. In order to determine directions of downhill flow on the surface, one converts radius to topography by subtracting the gravitational geopotential from the radius measurement. —MTZ, DES, JBA

For scale, the MOLA instrument’s receiver telescope has a diameter of a half-meter. The telescope is the circular silver object at the center of the image. Image: JPL/NASA
tor, Tharsis is a locus of volcanism and tectonism (faulting). The complex structure of Tharsis revealed by MOLA indicates that most of the topographic rise was formed by the intrusion and extrusion of volcanic material (as opposed to doming from upward-directed mantle forces).

The topographic map also shows Tharsis to consist of a primary rise that contains the Tharsis volcanoes (Ascraeus, Pavonis, and Arsia) and a secondary rise that comprises the Alba Patera volcanic structure and surroundings. In contrast to previous topography models, here, Mars’ largest volcano, Olympus Mons, is not associated with the main Tharsis rise but rather is situated off its western edge.

Prior to MGS, it was thought that Tharsis formed over most of the 4.5-billion-year history of Mars. However, geophysical modeling and stratigraphic analysis of ancient valley networks now show that most Tharsis magmas were emplaced during the earliest epoch of Martian history, known as the Noachian. Tharsis magmatism may have caused the release of vast quantities of carbon dioxide and water to the surface and into the atmosphere. Thus, the formation of Tharsis may have played a central role in contributing to early Mars’ possible clement climate.

**Surface Roughness**

Measurements of the spreading of MOLA’s backscattered pulses (see image on page 5) indicate an approximate bimodal roughness distribution, with a contrast across the geologic dichotomy boundary. High-latitude southern highlands, while rougher than the northern lowlands, are considerably less rough than equatorial highland regions.

The northern lowlands of Mars are now known to be the smoothest large-scale surface in the solar system yet measured by altimetry. The smoothness is likely explained by depositional processes (wind, water, and volcanic eruptions), but whether deposition was accomplished by, alternatively, wind-driven deposition or by sedimentation in an ancient ocean remains a subject of debate.

**Impact Craters and Basins**

MOLA topography has shown that the massive Hellas impact basin is the deepest known topographic depression in the solar system—more than 9 kilometers (6 miles) deep from the top of the rim to the bottom of the basin. MOLA’s global map shows the concentric distribution of cratered highland material around the basin, which rises above its surroundings 2 kilometers (about 1 mile) and accounts for a significant amount of the high-standing topography of the southern hemisphere. Material excavated from Hellas represents a major re-distribution of the Martian crust, contributing in part to the features along part of the dichotomy boundary.

MOLA data also verified the existence of the Utopia basin, buried beneath the northern plains. Similar in
diameter to Hellas but only 2.5 kilometers (1.63 miles) deep, Utopia was, on the basis of geologic mapping, proposed originally as an impact structure, although not resolved as such in pre-MOLA topographic models.

In addition, MOLA's high-resolution global grid has resolved numerous subtle, degraded, and previously unrecognized impact basins. In number and size, these partly buried craters indicate that beneath their resurfacing, Mars' northern lowlands are at least as old as its southern highlands. Thus, the crust in the northern lowlands and the crust in the southern highlands must have formed nearly contemporaneously.

Past Water
Early on, spacecraft images yielded abundant evidence for flowing water on the surface of Mars during the planet's youth, but many questions remain regarding the amount, duration, and possible episodicity of the flow of liquid water on the surface. Such questions bear significantly on the nature of Mars' early climate.

It is now known that the basic shape of the planet formed relatively early, so present-day topography can be used to infer approximate past pathways of water. For example, MOLA data reveal a continuous flow route from the Argyre basin to the Chryse outflow region, illustrating the south-to-north transport noted previously. Depending on the amount of water on the surface in the past, as much as 90 percent of the surface area may have drained into the northern plains. High-resolution topographic images, such as shown in the image of the Chryse outflow region (on the cover of this issue), have provided evidence for sustained flow and multiple floods.

Polar Regions
MOLA models of the polar regions have yielded the best available estimates of the volume of present-day water on Mars. The southern ice cap is much smaller in extent than the northern, although layered deposits in the south extend much farther from the ice cap and exhibit a more asymmetric distribution than in the north. The relief of the southern polar cap is comparable to that of the northern cap.

The total amount of surface ice is roughly 3.2 to 4.7 million cubic kilometers. If you spread all this ice evenly over the entire planet, it would be 22 to 33 meters thick. Even accepting that both caps are composed of pure water-ice (in reality, there is also carbon dioxide ice, but specific relative quantities are unknown), this range is at the low end of previous estimates of the amount of water believed to have been present early in Mars' history. At high latitudes, MOLA coverage is so dense that the surface is oversampled. Nevertheless, the high resolution shaded relief images produced (above right) show the complex surface structure in the vicinity of the Chasma Australe feature in the southern cap's layered terrains.
Clouds and Snow
MOLA also has functioned as an atmospheric lidar (a visible- or near-visible-light analog to radar), providing the first measurements of the three-dimensional distribution of cloud fronts on Mars. MOLA detects clouds in two ways: by either reflection or absorption of the outgoing pulse. Unusually strong, clustered atmospheric reflections suggest precipitation of carbon dioxide snow under supercooled atmospheric conditions. Clouds are most commonly viewed at night over the winter pole, but weaker cloud reflections have been observed at all latitudes, mainly during twilight and also at night.

The absorptive clouds—defined by an absence of range returns due to atmospheric absorption of the outgoing pulse—are mostly associated with the advance and recession of the edges of Mars’ seasonal polar caps. Biweekly averaging of MOLA data has yielded the first direct measurements of carbon dioxide snow depth, with both polar regions accumulating a maximum of 2 meters near the winter poles.

Radiometry Mode
After successful operation for the duration of the MGS mapping mission, MOLA ceased active ranging to Mars on June 30, 2001, during the extended mission. The ranging function was lost after an oscillator in the receiver electronics failed. At the time, MOLA had been in space for 1,696 days, and the laser had fired more than 671 million times in space; the instrument had made approximately 640 million measurements of Mars’ surface and atmosphere.

MOLA continues to operate in passive mode, measuring the brightness of the Martian surface. For example, MOLA observed the reflectivity of seasonal changes in the southern hemisphere’s polar frost. The signal varies noticeably through the seasons due to the pattern of deposition and sublimation, and subtle reflectivity changes may indicate the crystal grain or particle size of the frost. Such observations will contribute to the understanding of volatiles and dust cycling on Mars.

Maria T. Zuber, a member of The Planetary Society’s Board of Directors, is a professor of geophysics and planetary science at the Massachusetts Institute of Technology and a senior research scientist at the Laboratory for Terrestrial Physics at NASA’s Goddard Space Flight Center. David E. Smith and James B. Abshire are scientists at the Laboratory for Terrestrial Physics.
The four large satellites of Jupiter are famous for their planetlike diversity and complexity, but none more so than ice-covered Europa. Since the provocative Voyager images of Europa in 1979, evidence has been mounting that a vast liquid water ocean may lurk beneath the moon’s icy surface. Europa has since been the target of increasing and sometimes reckless speculation regarding the possibility that giant squid and other creatures may be swimming its purported cold, dark ocean. No wonder Europa tops everyone’s list for future exploration in the outer solar system (after the very first reconnaissance of Pluto and the Kuiper belt, of course).

The surface is covered with ridges hundreds of meters high, domes tens of kilometers across, and large areas of broken and disrupted crust called chaos. Some of the geologic features seen on Europa resemble ice rafts floating in polar seas here on Earth—reinforcing the idea that an ice shell is floating over an ocean on this Moon-size satellite. However, such features do not prove that an ocean exists or ever did. Warm ice is unusually soft and will flow under its own weight. If the ice shell is thick enough, the warm bottom of the shell will flow, as do terrestrial glaciers. This could produce all the observed surface features on Europa through a variety of processes, the most important of which is convection. (Convection is the vertical overturn of a layer due to heating or density differences—think of porridge or sauce boiling on the stove.) Rising blobs from the base of the crust would then create the oval

**Scientists are hotly debating whether they prefer Europa with a thick or thin crust—hence, The Great Europan Pizza Debate. The answer may well determine what life-forms could develop in the subsurface ocean of the Jovian satellite and how we humans might explore this amazing body.**
domes dotting Europa’s surface.

The strongest evidence for a hidden ocean beneath Europa’s surface comes from the Galileo spacecraft’s onboard magnetometer, which detected fluctuations in Jupiter’s magnetic field consistent with a conductor inside Europa. The most likely conductor: a somewhat salty ocean.

**THE GREAT EUROPAN PIZZA DEBATE**

Although we cannot prove the existence of a subsurface ocean on Europa until we return with more sophisticated robots, most planetary geologists consider such an ocean likely. In fact, considerable effort has been devoted to determining the thickness of the floating ice shell. The shell could be only a few kilometers thick (the thin shell, or “thin crust,” model), or it could be 15 or more kilometers (9 or more miles) thick (the thick shell, or “thick crust,” model). Io may have been the original “Pizza Moon” (the first Voyager images made Io look like a pizza), but Europa may prove the ultimate pizza lover’s delight (or nightmare), with the thin-crust vs. thick-crust debate sometimes reaching fever pitch. Nevertheless, no conclusive case can be made from either model based on geologic evidence alone.

The thickness of Europa’s ice shell has dual significance. First, it could influence the chemistry of the ocean underneath and the form that biological materials or organisms there might take. Second, it will determine the strategies best used to explore the underlying ocean, assuming we wish to sample it directly. Before looking at new evidence regarding the thickness of the ice shell, let’s examine these issues.

The debate over life on Europa has focused on chemistry and sunlight. The chemistry of the ocean is unknown, but dark reddish materials on Europa’s surface may have emerged from ocean depths. Unfortunately, we are uncertain as to the composition of these materials. They could be hydrated salts or sulfates or possibly something we haven’t thought of yet. Organic hydrocarbon compounds could also be present on Europa, but none have been unambiguously identified on the surface in Galileo orbiter data.

Many terrestrial organisms depend on sunlight for energy to process food. Any ice shell more than a kilometer (0.6 mile) thick will not allow sunlight through. Yet, a thin shell might be disrupted, fractured, or melted locally, allowing ocean water and anything floating or dissolved in it temporary access to the weak sunlight at Jupiter. This could promote the development of photosynthetic organisms, the severe radiation dosage at the surface notwithstanding.

Given a thick ice shell, however, these processes would not happen or would happen so slowly as to limit their effectiveness at giving life a boost. Other, much slower geologic processes, such as convective overturn (also known as diapirism) become important in the case of a thick shell.

Some Earth organisms do not in fact depend on sunlight but, rather, utilize chemical energy. The most famous are the organisms found at the black smokers along the volcanic midocean ridges and also the bacteria discovered inside rocks deep within Earth’s crust. The central question relating to Europa is whether these unusual life-forms originated in such extreme environments on their own or whether they evolved from species on Earth’s sunny surface and then migrated to the ocean bottom or deep crust. If organisms can evolve...
independently of sunlight, the thickness of the ice shell on Europa is no longer critical to the question of the existence of life there, except that in that case, Europan life would probably be nonphotosynthetic. In Europa’s cold ocean, the most likely source of chemical energy would lie on the ocean bottom. Europa as a body is much denser than pure ice, and most of the interior must be composed of rocks. The total combined thickness of ice shell and water ocean is only about 150 kilometers (93 miles), so the ocean floor is evidently made of rock. We know even less about this rock than we know about the ocean, but if neighboring moon Io is any indication (see “The Rampant Volcanoes of Io” in the March/April 2002 issue of The Planetary Report), volcanoes might be found on the bottom of Europa’s ocean. (If there is volcanism on the rocky ocean bottom of Europa, it is not likely to be as extensive or frequent as on Io.) Even modest volcanism could create hot thermal vents on Europa’s ocean floor, and these could be havens for life.

Arguments about thick or thin crust aside, plans are afoot (or “afloot!”) to explore Europa’s ocean. Perhaps the most ambitious proposal has been to land a nuclear-fueled robot submarine on the surface—which, at the end of a tether several kilometers long, would melt its way down to the bottom of the ice shell. Once in the ocean, it could swim some distance and explore. A thin shell would make such projects more feasible and less expensive.

Right: This Galileo image of ice “rafts” in a region of Europa called Conamara Chaos could be evidence of a thin ice shell floating over liquid water. But these broken plates—the largest of them about 10 kilometers (6 miles) across—could also have formed over a large plume of soft ice rising from the lower part of a thick icy crust. In either case, the jumbled, hummocky material called matrix could contain frozen bits of Europa’s subsurface ocean.

Image: JPL/NASA

The setting Sun, reflected off Jupiter, lights this Europan night. A constantly moving subsurface ocean is probably responsible for the “jigsaw puzzle” look of the Galilean moon’s cracked, icy crust.

Painting: Mark A. Garlick
The thickness of the ice shell on Europa is of the existence of life there, except could probably be nonphotosynthetic. Most likely source of chemical energy Europa as a body is much denser than must be composed of rocks. The total and water ocean is only about 150 nun floor is evidently made of rock. rock than we know about the ocean, indication (see “The Rampant Vol 2002 issue of The Planetary Report), bottom of Europa’s ocean. (If there is bottom of Europa, it is not likely to be Even modest volcanism could create ocean floor, and these could be havens crust aside, plans are afoot (or “afin”!) as the most ambitious proposal has not submarine on the surface—which, meters long, would melt its way down ice in the ocean, it could swim some would make such projects more fea-

In this thin-crust scenario, Europa’s icy shell has broken, allowing water to seep up to the surface. The dim light from Jupiter illuminates Europan sea life swimming around a hot vent similar to the black smokers found near Earth’s ocean trenches.

Painting: David Hardy
We might not need to melt our way through to the ocean to sample it, however. Geologic processes may bring bits of the ocean up to the surface for us. Several geologic processes are candidates, depending on how thick the ice shell is. As mentioned earlier, heating could melt through parts of the ice shell, locally exposing ocean material (now frozen). Large linear cracks could do the same. Europa’s surface is covered with cracks, though the interpretation of their origin is highly controversial.

By contrast, if the ice shell is thick, it will convect, as described earlier. Convection allows parts of the lower crust to rise up near the surface. Any pockets or bubbles of the ocean that might be interspersed or trapped within the lower crust would then be brought up to the surface, where we could sample them directly. Many of the chaos regions and oval spots scattered across Europa’s surface may be evidence of such convection.

Finally, if a large enough impact crater forms on the surface, it might penetrate through the ice shell and blast bits of ocean directly onto the surface.

**THE CASE FOR A THICK ICE SHELL**

How thick is Europa’s icy shell? Drill cores through it—similar to those taken from the Greenland ice sheet for climate studies—would ideally answer this question, but setting up drilling operations on radiation-soaked Europa is prohibitively expensive. Nature provides a convenient drill-coring system for us, however, in the form of impact craters.

Impact craters form when comets or asteroids strike Europa’s surface. These explosive events excavate material from near the surface of the satellite. The depth of excavated material is related to crater size; larger craters excavate more deeply.

In the same way, the morphology of larger impact craters depends on the strength of the ice shell at greater depths. All rocks (and water-ice is technically a rock) have inherent strength, and this is what helps planetary impact craters remain deep over the eons. If the crust immediately beneath an impact crater is unusually soft, it will not have the strength to maintain the crater’s original depth and will collapse very rapidly, forming shallower craters.

If the crater is large and deep enough, it will “sense” a liquid ocean beneath it. Since liquid water has negligible strength, we might expect craters that penetrate near the ocean to totally collapse and have no topographic expression. (The crater does not have to actually reach the ocean for this to occur.) To apply this method, we must survey and measure craters of all sizes on Europa and search for such changes in morphology that reflect changes in the satellite’s ice shell and potentially its thickness.

For the past two years, my work has focused on mapping as much of the topography of Europa (and the other Galilean satellites) as possible from the Galileo images. I have used three techniques to measure crater shapes and depths on Europa. The first is stereo image mapping, which utilizes parallax shifts between exposures to measure heights and depths. The second is called photoclinometry,
which employs the apparent brightness of slopes on mountains and valleys to estimate the steepness of the slopes. Finally, by measuring the length of shadows cast by a few individual objects on the surface, we can determine the heights of those objects.

By surveying and measuring all available craters on Europa, of which we have identified more than 100 larger than 1 kilometer across, we can begin to use impact crater morphology to probe Europa’s icy shell. It is immediately evident from comparison of crater shape and morphology that large craters on Europa are not as deep as on sister satellite Ganymede. Further, the shapes of Europa’s craters change at two specific and well-defined diameters. Craters smaller than 8 kilometers (5 miles) appear normal—that is, similar in depth and appearance to those on Ganymede. Yet, craters larger than 8 kilometers across are less deep than they should be. The big change, however, occurs at 30 kilometers (19 miles): craters larger than this are flat but are surrounded by 10 or more concentric rings. The abrupt shift from regular craters to these multiring structures indicates a profound change taking place within Europa to which only the larger craters are sensitive. It turns out that the depth of this change is approximately 75 percent of the crater diameter. Hence, the depth of Europa’s ocean must be on the order of 20 kilometers (12 miles). It could be even deeper.

Evidence is mounting in support of the thick-ice view. Topographic maps I have made of roughly 15 percent of the surface of Europa reveal that chaos regions have a warped uplifted surface inconsistent with the thin-ice model. Also, the Europian surface in general has considerably more relief than was previously thought possible. Plateaus up to 1 kilometer (0.6 mile) high and depressions and troughs 500 meters and a few kilometers deep are highly unlikely to survive in an ice shell only a few kilometers thick. Much like oceanic ice on Earth, such topography would either melt away or disappear as the ice flowed laterally under its own weight. Although it is difficult to be precise with such data, they do support the conclusion that Europa’s ice shell is thick rather than thin.

WHAT’S NEXT FOR EUROPA?
Do tiny algae (or giant squid!) swim in Europa’s ocean? The answer depends on the origins of life itself as well as on the conditions on Europa over the past billion years or so. Do any volcanoes rise from the ocean bottom? Is the ocean salty or acidic? Has the ice shell ever been thin? Have organic molecules ever existed in Europa’s ocean? Can life originate without sunlight? We can’t begin to answer these questions without going back to Europa.

Scientists and engineers are looking at new exploration options, including searching for a clever way to determine the ice shell thickness and sample the ocean. One approach would be to land a seismometer and chemical analyzer on a geologically interesting spot. Seismic waves could then be used to precisely map the depth to the bottom of the ice shell, and possibly to the bottom of the ocean. Onboard chemical analyzers could search for organic molecules and potentially determine the chemistry of the ocean, one of the basic indicators of Europa’s prospects as an “inhabited” planet.

Our first task, however, is to complete the global geologic, geochemical, and geophysical map of Europa so that we can pinpoint potentially interesting landing sites. Priorities include confirming that the ice shell is in fact as thick as suggested by the crater analyses. Regardless of our ultimate exploration strategy, Europa remains one of the most compelling objects in our solar system.

Paul Schenk is a staff scientist at Houston’s Lunar and Planetary Institute. He specializes in studying the satellites of the giant outer planets, including Jupiter, and in developing topographic mapping techniques. On weekends, he is also a SCUBA and deep sea diver.
Breaking New Ground: Red Rover Goes to Mars

by Bruce Betts

Red Rover Goes to Mars began as a project associated with NASA’s planned 2001 Mars lander. Through a formal arrangement with NASA, The Planetary Society would be conducting the first-ever education experiment on a NASA planetary mission. This experiment grew out of the Society’s Red Rover, Red Rover project. Red Rover, Red Rover developed a LEGO educational product of the same name that allows students to build and drive simulated Mars rovers.

While participants will not actually drive rovers on the Red Planet, Red Rover Goes to Mars involves students and the general public in Mars exploration as never before. Like Red Rover, Red Rover, its sponsors include the LEGO Company in partnership with the Society and with Visionary Products Inc.

The failures of NASA’s Mars Climate Orbiter and Mars Polar Lander in 1999 eventually led to the cancellation of the Mars 2001 lander. This left Red Rover Goes to Mars without a home.

Then, after a period of uncertainty, NASA agreed to incorporate Red Rover Goes to Mars formally into the Mars Exploration Rovers (MER) mission. The mission will land two identical mobile rovers on the Martian surface in January 2004.
Even before NASA’s incorporation of our project into MER, the Society invited the public’s participation in Mars exploration. In February 2001, nine international students became the first members of the public ever to target planetary spacecraft imaging. At Malin Space Science Systems in San Diego, California, they targeted the Mars Orbiter Camera aboard Mars Global Surveyor. One area they chose to image revealed a cluster of boulders that continues to perplex scientists (see the May/June 2001 issue of The Planetary Report).

A year later, in February 2002, a group of eight Student Navigators (see the May/June 2002 issue of The Planetary Report) worked at the Jet Propulsion Laboratory (JPL) with the Field Integrated Design and Operations rover—the same vehicle that scientists are training with in preparation for the MER mission.


An essay contest is now in full swing with the goal of selecting an international set of students—designated Student Astronauts—to participate in mission operations at JPL. Never before have members of the general public been selected to participate directly in a NASA planetary mission. The essay contest is open to all students ages 13 to 17. Rules as well as application forms can be found at www.redrovergoestomars.org.

The selected Student Astronauts will rotate through mission operations at JPL in teams of two, with each team spending approximately one week at the facility. The students will receive specialized training prior to their participation in mission operations. This training will prepare them to be fully involved in two particular activities for each Mars Exploration Rover: working with the sundial and assisting the magnet team.

Calibration targets for the MER cameras will serve as sundials for educational purposes. Generally, sundials on Earth are stationary; in contrast, the MER sundials will be on moving rovers. Therefore, these sundials will lack hour marks. The Student Astronauts will process engineering data from the rovers that will allow them to place hour marks on images of the sundials based on the rovers’ orientation. They will also produce captions for these images.

The Student Astronauts will participate in each rover’s magnet team as well. Several magnets on the spacecraft will be collecting dust over the course of the mission. The students will assist team members in studying images of the dust on the magnets.

In addition, Student Astronauts will attend key science meetings that determine the commands sent to each MER spacecraft for its next day of activity.

Finally, these exceptional students will serve as ambassadors for the mission, much as actual astronauts do. Through a variety of media, including the Web, they will be communicating to the public what they observe.

Each of the two MER spacecraft will carry a DVD produced by The Planetary Society in conjunction with Visionary Products Inc., along with hardware and labor donations from Plasmon OMS. Each spacecraft will also carry the names of millions of people, through
NASA’s Send Your Name to Mars opportunity. (See www.redrovergoestomars.org for information and links; but hurry, the deadline is November 15, 2002!)

Each of the DVDs features a number of elements to better involve the public and especially children. These include colors and shades of gray that can be examined for how they look different under Martian lighting conditions. Also included will be a representation of a mini-robot that kids can relate to and that will facilitate creative child-related activities.

Additionally, the DVDs will contain passwords encoded using two-dimensional barcodes. Once deciphered from study of the first images transmitted from Mars, the passwords can be used to access additional activities.

Stay Tuned

Over the next year and a half, The Planetary Report will be informing you of still more opportunities for participation in Red Rover Goes to Mars. You can also keep up-to-date and check out detailed information on the project and the MER mission by logging on to our website, planetary.org.

Red Rover Goes to Mars is breaking new ground in many ways. It represents only the second privately contributed hardware on a planetary mission. (The first was The Planetary Society’s Mars Microphone on the failed Mars Polar Lander.) Also, it is the first educational experiment on a planetary mission. After a tough journey that saw a mission cancellation, Red Rover Goes to Mars now stands poised to reach out to the world as part of an even more exciting mission: NASA’s Mars Exploration Rover mission.

Through Red Rover Goes to Mars, the level of public and student participation in a NASA mission is also unprecedented. The international scope of the participation is significant as well. Plus, The Planetary Society has successfully engaged a large, child- and learning-focused company in an educational project—yet another precedent in planetary exploration.

Bruce Betts is director of projects for The Planetary Society and project manager for Red Rover Goes to Mars. He is also a planetary scientist.
Earth Orbit—Another shipwreck in the ocean of space: the CONTOUR (Comet Nucleus Tour) spacecraft, launched on July 3, was lost in mid-August. Bound for two comets, Encke and Schwassmann-Wachmann 3, the spacecraft had spent six weeks in Earth orbit, increasing energy and aligning its orbit geometry for the desired interplanetary trajectory.

Injection to the interplanetary trajectory required a rocket burn—and that, apparently, caused the spacecraft to break apart. Mission controllers received no telemetry after the solid-rocket burn. Earth-based telescopes were able to pick out three objects traveling near where the spacecraft was supposed to be, which leads engineers to suspect that the spacecraft broke up, or something broke off it, as a result of the solid rocket motor firing.

NASA has appointed a special accident investigation commission to determine the cause of the failure. The Johns Hopkins University Applied Physics Laboratory (APL), which was responsible for the mission, will conduct its own internal review.

The loss of CONTOUR is a big setback for planetary exploration. CONTOUR is the first Discovery mission to be lost in the “faster, better, cheaper” program instituted in the 1990s by then–NASA Administrator Dan Goldin. The Mars Climate Orbiter and Polar Lander were also “faster, better, cheaper” projects, although part of a different program, and some pundits claim these failures prove that achieving all three goals in a single mission is impossible. But there have been successes, too. We are still getting results from Mars Global Surveyor and Mars Odyssey and have enjoyed success with Mars Pathfinder and NEAR Shoemaker. Generalizations are not easy to make.

The loss of CONTOUR is also a blow to planetary science. Comets are remnants of solar system formation and can tell us much about the system’s origin. We owe much of our oceans—and perhaps even ourselves—to comets. Yet, information about them is hard to get, and although they come our way frequently, missions to them are rare due to political and programmatic complexities.

Future comet missions are planned—the European Rosetta will launch in 2003, and the US’s Deep Impact is planned for 2004—but these missions won’t reach their targets for many years.

The CONTOUR science team, led by Joe Veverka of Cornell University, has proposed building CONTOUR 2—a replacement craft to launch in 2006. Considerable money will be saved if identical copies of the spacecraft and instruments can be built. Whether or not a credible case can be made for rebuilding the spacecraft and recovering the lost science will depend, in part, on the reasons for failure.

The New Horizons mission to Pluto and the Kuiper belt, planned for launch in 2006, might also be affected by the CONTOUR loss. Built and managed at APL, the New Horizons spacecraft uses components inherited from CONTOUR. Its future hinges on the action Congress will soon take. If it is to fly, New Horizons must be added to the NASA budget over the Bush administration’s objections (see next item).

Through all this, we must remember that space exploration is an adventure—replete with both accidents and triumphs. We are disappointed but not downcast about the loss of CONTOUR. We extend sympathy to the team that labored long and hard to make it happen, but we remember that the losses of Mars Observer and other missions were followed by the riches we are now receiving from Global Surveyor and Odyssey.

Washington, DC—The Appropriations Committee of the US House of Representatives joined its Senate colleagues in providing funds for the Pluto–Kuiper belt mission, then went one step further by adding money to reinstate the development of the Europa orbiter. If passed by the full Congress, we will have been completely successful in our effort to overturn the Bush administration’s plan to cancel both missions in fiscal year 2003.

We are now sending a copy of our petition in support of the Pluto and Europa missions, signed by more than 10,000 people, to every member of Congress. To accommodate all the signatories to the petition, we had to use very small type. Using normal-size type for all of Congress’ copies would have taken about 18,000 pages!

The timing of congressional action is uncertain. As we go to press, congressional staff are indicating that the appropriations bill will probably not be considered until after the November elections.

The new fiscal year started on October 1 without a budget. During the interim period, Congress provided a temporary bill to fund government operations. The Pluto–Kuiper belt mission has sufficient funding only through November, so its fate may depend on a bigger political battle between the White House and Congress after the November elections.

For the latest information on the continuing fight to save the Pluto and Europa missions, see our website, planetary.org.

Louis D. Friedman is executive director of The Planetary Society.
Do solar sails reflect light (visible and infrared) from both sides? Also, can the light reflected from Earth be measured, and is this amount of light significant for Cosmos 1?
—M.B. Melcon, Durham, California

Solar sails do reflect light from both sides, but for The Planetary Society’s Cosmos 1 solar sail, the amounts are very different. A deposit of aluminum on one side of the solar sail film creates a highly reflective surface (see photos below). This side reflects 80 to 90 percent of the light that hits it, which makes it efficient in producing thrust. The other side of the solar sail, which is not coated with aluminum, is much less reflective and, therefore, would produce much less thrust. Infrared light also reflects from both sides of the sail material, but the amount of light reflected depends on its wavelength. Most of the Sun’s energy is in the visible and very near infrared parts of the spectrum.

It is possible to measure the light reflected off Earth from space, although Cosmos 1 will not do so. The amount of sunlight reflected from our planet will not be a major factor in the thrust of the solar sail, because rarely will the sail be pointed in a direction to receive much light from Earth. If the sail were pointed that way, the light reflected from Earth would produce a thrust that would move Cosmos 1 at an angle inclined to the sail’s orbit. It would not produce much change to the orbital energy of the spacecraft.
—LOUIS D. FRIEDMAN, Cosmos 1 Project Director

Most extrasolar planets found at large distances from their stars appear to have eccentric orbits. What implications might there be for the long-term stability of these systems? Can planets with stable orbits within the “habitable zone” exist within them?
—Tom Koleszar, Calgary, Canada

The stability of a planetary orbit is a complicated function of the planet’s period, eccentricity, mass, and the orbits and properties of the other planets in the planetary system. Many eccentric orbits are so unstable, the planet is rapidly flung into an orbit close enough to its parent star that its temperature rises considerably, or it gets tossed out to orbital distances where its temperature is never above freezing. There are also possible combinations of planetary masses and orbital properties in which highly eccentric orbits can be stable for billions of years.

However, life might not develop on planets with stable but highly eccentric orbits. On such planets, the temperature goes from boiling to freezing as the planet rapidly approaches the star and then recedes. For life as we know it to evolve, liquid water is needed, and the temperature must not be so hot that biomolecules are destroyed, nor so cold that chemical reactions needed for metabolism stop. Still, if there are habitats on these planets that avoid severe temperature swings, it’s conceivable that life could start there.

We know from the study of living things on Earth that life is found across
many different habitats and in a very large temperature range. Life exists in the depths of the sea, buried many kilometers deep in rock, and on the surface where temperatures fluctuate from hot to cold and back again. Some bacteria thrive at temperatures well above boiling in the hydrogen-sulfide-laced waters at the bottom of Earth’s oceans, where no light ever penetrates. But life is also found below the ice layer in Antarctic lakes, whose surfaces have been frozen for thousands of years. When environmental conditions become too extreme, then bacterial spores, plant seeds, and simple animals become dormant, and they revive once conditions again become favorable.

Higher-level animals can also adapt to the extreme temperatures that range from winter in Minnesota to summer in Arizona, as well as to the smog-laced atmosphere of Los Angeles. Clearly, we find life on Earth where we wouldn’t expect to. Hence, it is reasonable to expect life to exist on planets where extreme temperature ranges accompany highly eccentric orbits—if those planets also harbor pockets of liquid water.

—WILLIAM BORUKI, NASA Ames Research Center

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**Factinos**

 Scientists have developed an atmospheric model that lends insight into decades-old mysteries surrounding Saturn’s moon Titan. This research could shed light on the chemical processes that may have jump-started life on Earth.

Titan has long puzzled scientists because of several unexplained features in its thick, hazy atmosphere, which is composed mainly of solid organic materials. But even more baffling is a layer of Titan’s haze detached from its atmosphere, thus resembling a ghostly shell floating in space.

“Titan is an interesting world. Its organic haze may be an example of the prebiotic organic chemistry that led to life on Earth,” says Chris McKay of NASA’s Ames Research Center. McKay is coauthor of “A Wind Origin for Titan’s Haze,” which appeared in the August 22, 2002 issue of Nature.

In the Nature article, McKay (who is also on The Planetary Society’s Board of Directors), Pascal Rannou of the Universities of Paris and Versailles-St. Quentin, and Frederic Hourdin of the University of Paris provide the first “coupled” model of Titan, linking the moon’s organic haze with atmospheric winds and with the sunlight that heats the haze.

“We found that the main features of Titan’s organic haze arise from a strong feedback loop between the haze, the sunlight, and the wind,” says McKay. “This is a critical new factor in understanding Titan.”

—from NASA Ames Research Center

On July 4, 2002, Konrad Dennerl of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany captured the first-ever X-ray image of Mars. He used the Chandra X-Ray Observatory to obtain the picture at right. Dennerl’s accomplishment is not unexpected since Venus, Jupiter, Earth, and even comets shine (although faintly) in X-rays.

Dennerl’s computer simulations even predicted that our rusty neighbor would look about 25 percent brighter in X-rays along its sunlit limb—something Chandra did indeed observe. “There was a remarkably good match between expectation and observation,” he concludes.

—from Sky & Telescope

**The first-ever X-ray view of Mars was taken by the Chandra X-Ray Observatory on July 4, 2001. The planet’s day-night terminator is located near the left edge of this slightly gibbous disk.**

Image: Courtesy of Konrad Dennerl, Max Planck Institute for Extraterrestrial Physics

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Chamber, a stainless-steel vacuum container believed to be the largest instrument dedicated to space simulation research on a North American campus.

So far, the Andromeda Chamber studies indicate low levels of methane production, which means the organisms are metabolizing under low pressures. These results suggest that Martian life would be able to survive at such pressures, since Mars’ atmosphere is much less dense than Earth’s. To read more about these experiments, visit http://advancement.uark.edu/news/2002/AUG02/Life_on_Mars.html.

—from the University of Arkansas
Announcing Red Rover Goes to Mars
On October 15, The Planetary Society announced its participation in NASA’s Mars Exploration Rover mission with a Red Rover Goes to Mars Student Astronaut Contest and a spacecraft DVD assembly (see “Breaking New Ground: Red Rover Goes to Mars,” on page 16). The announcement took place at the World Space Congress—the joint gathering of the International Astronautical Federation, with associates the International Academy of Astronautics and the International Institute of Space Law, and the Committee on Space Research. The gathering, held at the George R. Brown Convention Center in Houston, Texas on October 10–19, was attended by 13,000 scientific, technical, business, and government leaders representing every facet of the international space community.

The Red Rover Goes to Mars Student Astronaut Contest will build on precedents set by Planetary Society programs Red Rover Goes to Mars Student Scientists and Student Navigators (see the May/June 2001 and 2002 issues of The Planetary Report). An international essay contest will help select a group of talented young people to participate in operations of the Mars Exploration Rover mission in early 2004. (For more information, visit www.redrovergoestomars.org.)

With the support of the LEGO Company, The Planetary Society is providing two spacecraft DVD assemblies to the Mars Exploration Rover mission. These DVDs will carry to the surface of the Red Planet the names of millions of Mars enthusiasts from around the world. Until November 15, 2002, names are being gathered by NASA at http://spacekids.hq.nasa.gov/2003/.

NASA’s twin Mars Exploration Rovers are designed to study the history of water on Mars. The identical rovers, which are scheduled for two separate launches between May 30 and July 12, 2003, will land in two different locations on the Red Planet in January 2004.

The Planetary Society and the LEGO Company jointly hosted a large booth in the World Space Congress Exhibit Hall. This booth featured an engineering model of the spacecraft DVD, a full-scale model of a Mars Exploration Rover built entirely of LEGO bricks, and a remote-controlled LEGO MINDSTORMS rover, which visitors were invited to try their hands at navigating.

—Emily Stewart Lakdawalla, Science and Technology Coordinator

Expedition to Argentina
We are still planning an expedition to Argentina to study some interesting outcrops in Patagonia. At this writing, we are expecting to depart sometime after February 2003. If you’re interested in the expedition—even if you’re just curious and want to know more—please call Lu Coffing at (626) 795-5100, extension 234, or e-mail her at lu.coffing@planetary.org.

—Lu Coffing, Financial Manager

The Society at European Mars Society Convention
Society Executive Director Louis Friedman gave the plenary closing talk to the European Mars Society convention in Rotterdam, Netherlands on September 30, 2002. Friedman spoke about the pioneering Cosmos 1 solar sail project, which the Society is conducting with the sponsorship of Cosmos Studios and the A&E network. Convention organizers cited Cosmos 1—the first space mission ever attempted with private funding by a space interest organization—as an inspiration to the goals of the European Mars Society, which seeks citizen involvement in space exploration missions.

Friedman also gave a presentation at the European Space Agency’s European Space Technology Center in the Netherlands. Next year’s launches of the Mars Express and Rosetta missions make Europe a major player in planetary exploration—a welcome and important step for the Society’s worldwide membership.

—Susan Lendroth, Manager of Events and Communications

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The Planetary Society has been working with planetariums around the world to establish discounts ranging from 15 to 100 percent off admission prices for our members. For a complete list and more specific information, visit http://planetary.org/html/member/planetariums.html, or call Linda Wong at (626) 793-5100, extension 236.

If a planetarium near you is not on our list, please let us know at tps@planetary.org.

—Linda Kelly, Program Development Manager

Thank You
We would like to gratefully acknowledge a recent bequest by Michael Sosnowski, a member since 1998. The gift in his name supports the Society’s Near Earth Objects programs.

Over the years, bequests have allowed The Planetary Society to fund special projects and to pay for much-needed equipment. If you would like information about making a bequest to the Society, call Lu Coffing at (626) 793-5100, extension 234, or e-mail her at lu.coffing@planetary.org.

—LC
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On a list of Mars' topographical charms, its huge volcanoes rank high—and none more so than Olympus Mons. About 100 times larger than Hawaii's Mauna Loa, Olympus Mons covers an area the size of Arizona. Kees Veenenbos' computer-generated portrait of Olympus Mons is based on topographical data from the Mars Orbiter Laser Altimeter (MOLA) on board Mars Global Surveyor.

Kees Veenenbos uses MOLA data to produce a variety of still images and animations of Mars. His views of the Red Planet range from realistic renderings of how it looks today to visualizations of it as a much warmer and wetter place—how it may have existed about 3.5 billion years ago. Veenenbos' work has been published in scientific magazines, papers, and other media all over the world.