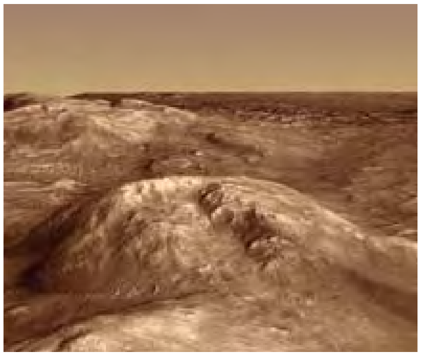
Solar system mapping

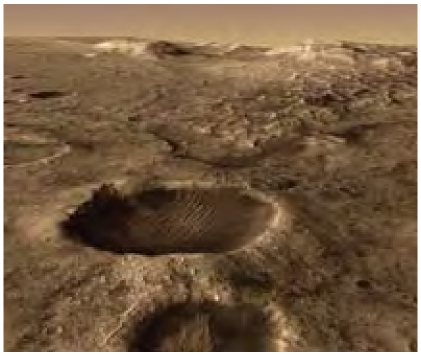
ELECTRONICS & INTEGRATED SOLUTIONS

CASE STUDY

Agency employs photogrammetric technology to study and map geologic features of the solar system

Customer: U.S. Geological Survey (USGS)
Industry: Planetary sciences





Perspective views of the Columbia Hills inside Gusev Crater as seen from the north (top) and southwest (bottom), based on stereo analysis of High-Resolution Imaging Science Experiment (HiRISE) images. The images are false-colored to approximate the appearance of Mars and vertically exaggerated 1.5x. The Mars Exploration Rover (MER) Spirit climbed over Husband Hill, shown in the top image, and is currently exploring Home Plate, which is just visible beyond it. The rover's panoramic view from the summit of Husband Hill appears across the top of this page.

Background

The USGS is the primary producer of digital and hardcopy planetary maps in the U.S. Its Astrogeology team, based in Flagstaff, Arizona, studies the properties and evolution of planets and their satellites, asteroids, and comets. Using images and samples collected by spacecraft expeditions, USGS researchers analyze and measure soil, water, terrain, atmospheric conditions, and other properties that characterize objects in the solar system. Results of these studies are used to construct topographic, geologic, and thematic maps, globes, digital elevation models (DEMs), and 3D-flythrough simulations to support geophysical studies, education, and the planning and operation of subsequent missions.

The opportunity

Mars is approximately half the size of Earth. Its surface is dotted with impact craters and covered with surprisingly Earthlike, but often very large, features such as volcanoes, canyons, polar caps, and channels. The current atmosphere is thin, cold, and dry, but the channels and other features hint that water flowed on the surface at one time, and may have temporarily formed oceans. These features distinguish Mars as the solar-system body most similar to Earth in its surface properties. The continuing investigation of Mars may thus fill gaps in our understanding of planetary conditions under which life can originate and flourish, and the climatic shifts that can lead to its demise.

The challenge

Since its formation in the early 1960s, the USGS Astrogeology team has amassed large collections of imagery and supporting data. Synthesizing these data into maps that can be used by scientists, engineers, and the general public has always been one of its primary — yet most challenging — roles. Raw legacy images of Mars, the moon, and other targets from early missions retain great value, and have yet to be superseded in resolution for some areas in some cases.

The first space missions relied on photographic film. Digital imaging supplanted photography in the 1970s, but even as late as the 1980s, most map products were the result of analog processing, manual measurements, and other human syntheses of image data. Early base maps consisted of unrectified photomosaics produced by hand. Additional images were used to interpret missing details, and shaded relief drawings were created by airbrush. Topographic contours were painstakingly collected from stereo imagery on analog plotters, and maps were produced at a range of scales from global to local.

In the past decade, pushbroom imagers have largely superseded framing cameras for orbital reconnaissance. The size of individual images has jumped from the megapixel to gigapixel level, and the total volume of imagery from moon and Mars missions planned for the next few years is expected to reach hundreds of terabytes. Today, stereo-imaging capabilities are built into many orbital scanners and most framing camera systems on landers and rovers; the latter now carry microscopes of ever-increasing power. Hyperspectral imagers provide

compositional information that must be georeferenced, while radar images unveil the cloud-shrouded surfaces of Venus and Saturn's giant satellite Titan, and may soon reveal whether useful deposits of water ice are trapped in the permanent shadows near the poles of the moon. Finally, laser altimetry has become an essential tool in planetary mapping, as dense global datasets provide the most precise definition of geodetic coordinates to which images and other data must be tied to make more detailed maps.

The solution

USGS staff are involved in all stages of the planetary exploration and mapping process — in many cases they help to design, build, and test innovative new camera systems. Once images and supporting data are safely on Earth, they must be catalogued, processed into map products, and delivered to the customer. Ultimately, products go to NASA's Planetary Data System, where they are archived for future users, but the immediate customer is often a team running another mission, urgently in need of maps to plan its next day, week, or year of exploration. Flexibility and efficiency of the mapping software are therefore key concerns.

The USGS has chosen an approach that makes synergistic use of both public domain software written in-house, as well as commercial photogrammetric software. It uses BAE Systems' SOCET SET® to accomplish its planetary mapping tasks, and its own system, Integrated Software for Imagers and Spectrometers (ISIS), provides an end-to-end capability for processing planetary images into orthophoto mosaics for use as base maps. By writing the software in-house, the USGS maintains the flexibility to read, decompress, calibrate, and model data geometrically from each new sensor as it becomes available.

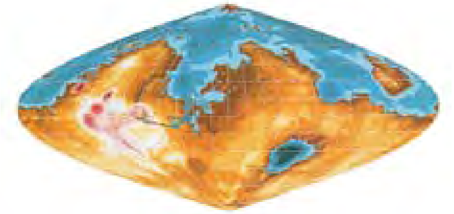
ISIS is built to use the special format known as Spacecraft and Planetary ephemeredes, Instrument C-matrix and Event (SPICE) kernels to store all orientation data for NASA and many foreign planetary missions. ISIS incorporates the bundle adjustment software that has been used over the past several decades to define the geodetic control networks of 23 planets and satellites, and to tie hundreds of thousands of images into these networks. Finally, ISIS offers cutting-edge tools that researchers can use to analyze the photometric and spectroscopic content of images. The USGS has developed a production capability for shape-from-shading (photoclinometry) that can be used to make DEMs from single images (where the surface reflectivity is uniform), or to refine stereo DEMs by adding detail down to the limit of image resolution.

For stereo analysis, the USGS turns to commercial software. ISIS programs translate the images and SPICE orientation data into formats that SOCET SET can recognize. The production and quality control of stereo DEMs and orthoimages is carried out in SOCET SET's general-purpose digital photogrammetric workstation (DPW) environment.

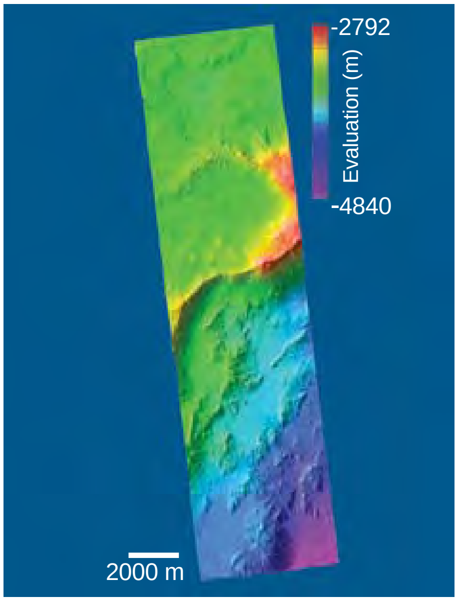
The DPW provides a complete workflow, including:

- Modules for multi-sensor triangulation
- Automatic stereo matching using the automatic terrain extraction (ATE) module to generate DEMs
- Quality control and DEM editing with stereo viewing using the interactive terrain editing (ITE) module
- Tools for map finishing and data analysis that complement those in ISIS

ATE is exceptionally flexible and can be tuned to produce detailed DEMs from images of widely varying size, quality, and scene content. The ITE module was an equally important factor in



The USGS produced the global topographic map of Mars, above, from nearly 1000 Viking Orbiter images by conventional analog photogrammetric methods. A team of analysts labored for most of the 1980s to complete this product, which has a post spacing of 1 km, though most of the points are actually interpolated from widely spaced contours. The topographic model below, based on a single HiRISE stereo pair, contains approximately the same number of height points, spaced 1m apart. Using SOCET SET®, its production required 60 hours of automated matching and 90 hours of interactive quality control and editing. The model shows debris flows associated with the central peak of the Mojave crater. Modern digital processing methods, including SOCET SET, make it practical to process gigabytes of image data for an individual research project.



the Astrogeology team's selection of SOCET SET. A final interactive viewing and editing step is essential to guarantee the quality of DEMs produced automatically. It sometimes is the only way to make DEMs from image sets that are small in size but large in scientific value, such as the Huygens probe's close-up images of Titan's surface.

Flexible, generic sensor models included with SOCET SET are instrumental in supporting analysis of the full range of framing cameras and pushbroom scanners flown to the moon and planets. The USGS continually works closely with BAE Systems to improve this modeling. The C++ programming environment of the SOCET SET Developer's Toolkit (DevKit) has enabled the USGS to extend these built-in capabilities by writing its own sensor models for unique instruments, such as the imaging radars flown to Venus and Titan. One of the advantages of using SOCET SET is that pushbroom scanner data, frame images, and custom-modeled radar scenes can be mixed freely in the bundle adjustment and DEM-generation steps, providing opportunities for synergistic use of differing datasets. In addition to modeling unique sensors, the USGS uses the DevKit to write some of the software used to import data from ISIS into SOCET SET, and to export DEMs and orthoimages back to ISIS.

Conclusion

Owing to the availability of new software technology such as ISIS and SOCET SET to create a powerful, systematic framework for processing image data, the USGS has made remarkable progress in refining solar system map production. Older maps, produced by laborious manual methods, are superseded as well as complemented by the new, much-more-accurate output products available from digital cameras such as High-Resolution Stereo Camera (HRSC), Microscopic Imager, and High-Resolution Imagining Science Experiment (HiRISE) camera in the powerful ISIS/SOCET SET environment. SOCET SET's versatility as an end-to-end digital photogrammetric workflow, with especially strong functionality in the areas of ATE and ITE, is ideal for generating these deliverables, but the key component is SOCET SET's DevKit, which enables programmers to customize the product to work with unique datasets.

Perspective views of Victoria Crater from the southwest. Top image shows a 0.3 m-per-pixel color image from HiRISE that has been draped over a 1 m DEM made from a HiRISE stereo pair, with no vertical exaggeration. Bottom image shows a close-up view of Duck Bay, where the MER Opportunity will attempt to enter the crater and study the sediments exposed in its walls. Slope measurements based on the HiRISE DEM were critical to determining the safest point of entry. The rover itself is barely visible on the far side of Duck Bay in this image, taken in 2006.

Mars, the "Red Planet," named by the Romans after their god of war (because of its blood-like color), has always been a major focus of extraterrestrial exploration because of its geologic similarity to Earth and its potential for life.

Early planetary geology studies in Flagstaff were led by Eugene Shoemaker, recognized by many in the field as the father of planetary geology (as a discipline distinct from astronomy). Shoemaker founded the branch of Astrogeology within the USGS in Flagstaff in 1965, where much of the original use of photogrammetry and remote sensing to measure and map the solar system took place. After his death in 1997, a vial of his remains was carried to the Moon by the Lunar Prospector, making him the first human to be interred on another world.

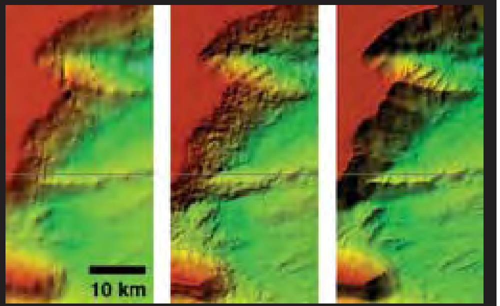
Highlights of Mars imaging

Highlights from three current Mars missions provide an idea of the wide range of data that the USGS is analyzing with SOCET SET® and ISIS. The first of these spacecraft to reach Mars, in December 2003, was the Mars Express orbiter. USGS scientists are part of the team for the HRSC, the first camera designed explicitly for photogrammetric mapping to be flown to another planet. The nine-line scanner design of the HRSC allows collection of multi-angle stereo images, as well as four color bands in a single pass. The ground sample distance ranges upward from 12.5 m; nearly two-thirds of Mars has been imaged at 50 m-per- pixel or better. In a detailed comparison between stereo DEMs produced at several member institutions, SOCET SET compared well with automatic matching algorithms on the cutting edge of research, and was the only complete system providing its own bundle adjustment solution and the possibility of interactive DEM editing. The USGS group was the first to demonstrate refinement of the stereo DEM with shape-from-shading.

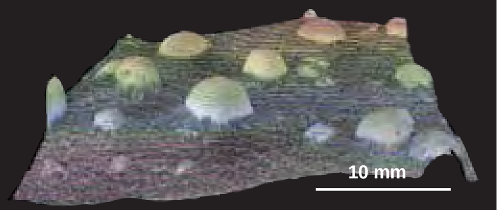
Mars Express was followed closely by two NASA Mars Exploration Rovers (MER), Spirit and Opportunity, which landed on opposite sides of Mars in January, 2004. Both are still operating, nearly three years into a mission planned to last only 90 days. Eight cameras arranged as stereo pairs are used to navigate the rovers to targets of scientific interest, reconstruct their paths, and map out the spectral properties of geologic features. The primary responsibility of the USGS, however, is for the ninth camera: a Microscopic Imager (MI) carried on the end of each rover's robotic arm. The MI views a 3-cm-square area at 30 micrometers per pixel. Imaging sequences commonly include motion toward or away from the target (to bring different areas into correct focus), and motion across the target surface to build up overlapping coverage that can be used to produce stereo DEMs and image mosaics. Registering the MI images to the much-lower-resolution color images from the rover's other cameras, and integrating the close-ups of patches of rock and soil into the many coordinate systems used to track the rover's motions across Mars, constitute novel challenges.

The largest spacecraft ever sent to Mars, the NASA Mars Reconnaissance Orbiter (MRO), arrived at Mars in March, 2006, and entered its mapping orbit in November. From this low orbit, the HiRISE camera scans the surface at a scale of 0.3 m-per-pixel. The camera uses multiple, overlapping detectors to build up a pushbroom image 20,000 pixels wide, with three-color bands covering the central 4000 pixels. Unlike HRSC, the instrument does not have a built-in stereo capability, but stereo pairs can be acquired by rolling the entire spacecraft to either side to re-image a target on a later orbit. The HiRISE team plans to take at least 1000 such stereo pairs, totaling roughly two trillion pixels, and covering perhaps 0.1% of the surface of Mars. The USGS is using SOCET SET to make DEMs from a small fraction of these pairs, focusing on providing the MER team with detailed maps of their rovers' locations and validating the safety of candidate landing sites for the next generation of landers and rovers.

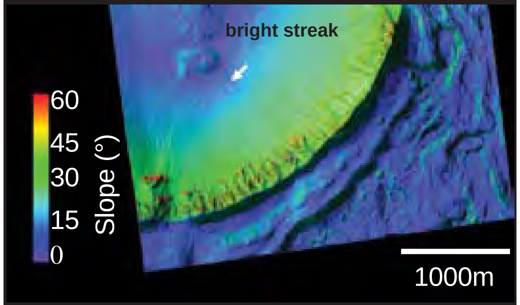
The vast size of the HiRISE images is the primary challenge. Fortunately, the high signal-to-noise ratio, along with the density of surface features, ensures that automatic matching works well. The USGS has written software to synthesize the separate channels into the view as seen by an idealized camera with a single, giant pushbroom array. A final difficulty arises in tying such high-resolution imagery to the laser altimeter ground control. With HiRISE, and even with somewhat lower-resolution sensors, such as HRSC, it can be difficult to identify and localize features in the altimetry dataset that can be used as control points. Importing not only the interpolated altimetry contours, but also the altimeter ground tracks, into SOCET SET is critical to locating well sampled features that can be used for horizontal, as well as vertical, control.



Color-coded, shaded relief maps of part of the "Martian Grand Canyon," Vallis Marineris, show the improvement in detail that Mars Express HRSC images provide. Left: laser altimetry data are the best global topographic dataset for Mars. Center: HRSC stereo DEM, produced in SOCET SET. Right: USGS shape-from-shading software adds additional detail to the stereo DEM. Total relief in the area shown is approximately 3 km from green to red.



Hematite-rich "blueberries" revealed by the MI onboard the MER Opportunity. Contour interval 0.25 mm; no vertical exaggeration.

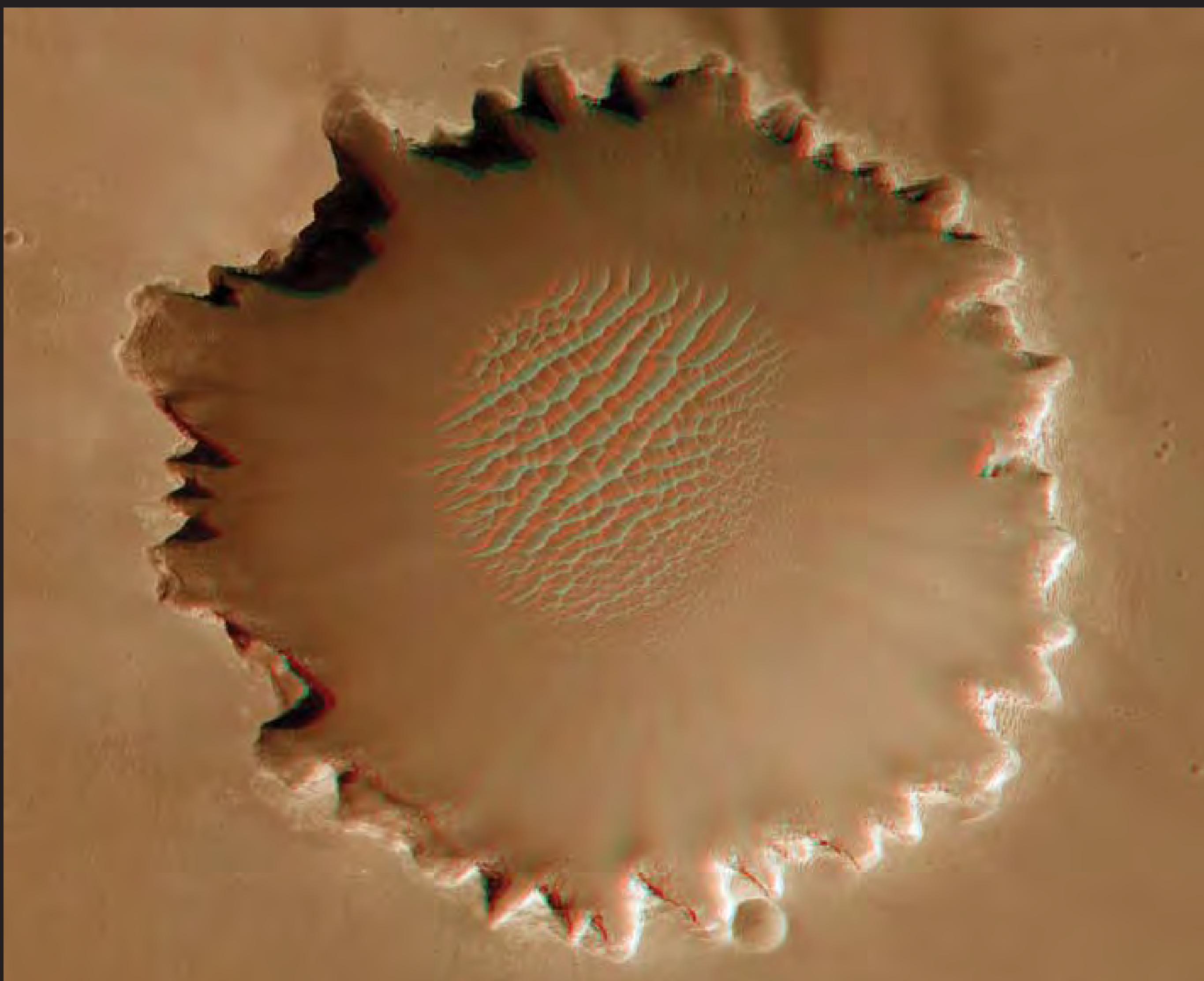


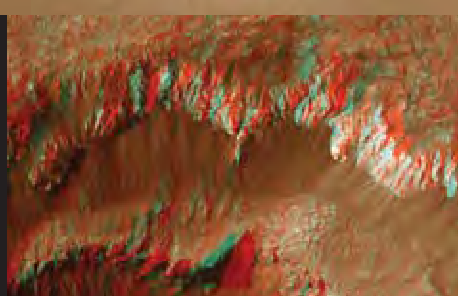
This impact crater in the Centauri Montes region has achieved celebrity because before/after images indicate that a bright streak of material flowed down the crater wall within the past few years. Topography and slopes (shown here in color, superimposed over the HiRISE image) are being used by scientists to model the formation of the streak and assess whether it was merely a dry debris flow or involved the release of ground water.

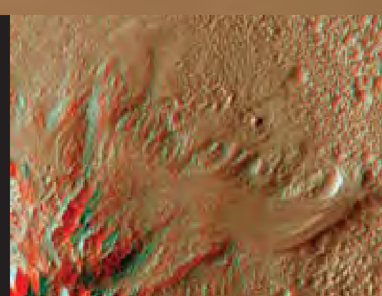
Images courtesy of the USGS.

For more images and information, visit: http://astrogeology.usgs.gov/

Anaglyph of Victoria Crater







Use the 3D glasses provided to view the image in stereo