Visualization Tools Facilitate Geological Investigations of Mars Exploration Rover Landing Sites

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Figure 1: Impact crater imaged by NASA's Mars Exploration Rover Spirit (NASA/JPL/Cornell http://photojournal.jpl.nasa.gov/catalog/PIA05570).

Abstract

The current rate of Mars exploration data acquisition demands that geoscientists and computer scientists coordinate central storage, processing and visualization strategies to anticipate future technological advancements. We investigate how existing 3-D visualization tools can be used to study a part of the Mars orbiter and lander data (about 4 terabytes of data). Our tools assist in juxtaposition of different datum and in viewing data that spans multiple orders of magnitude, specifically for current scientific research pertaining to Mars' geophysics and geology. These tools also permit effective data fidelity and resolution assessment, allowing quick identification of problems related to the use of differing spatial coordinate systems, a continued problem. Knowledge gained from the small dataset we test, helps us identify key tools needed to accommodate the technology required to process and analyze approximately 64 terabytes of Mars data expected by 2008. We use the current planetary data archives, and identify key visualization techniques and tools that distill multiple data types into manageable end products. Our goal is to broaden the user base, using readily available platform-independent freeware packages, while simultaneously including sufficient modularity to be compatible with future technologies.

CR Categories: Feature Detection, Virtual Environments, and Terrain Visualization.

Keywords: Earth, Space and Environmental Sciences Visualization.

1. Introduction

The exponential increase in Mars data over the past decade including imagery, topography, gravity, magnetic, and geochemical data sets, necessitates development of versatile visualization tools and data reduction methods. The Mars Exploration Program (MEP) encompasses a series of missions with launches through and beyond 2005, which will continue to produce unprecedented volumes of data, presenting opportunities for breakthrough research and unique avenues to promote public interest in space exploration (http://wwwpds.wustl.edu/missions/mep/). To date, Mars Global Surveyor and Mars Odyssey (two spacecraft currently in orbit around Mars) have already generated approximately 3.7 terabytes of data. The Mars Exploration Rovers (MER), Spirit and Opportunity, are projected to return 105 gigabytes during their nominal three-month lifetime in 2004 and Mars Reconnaissance Orbiter over 64 terabytes by 2008, with a total of more than 300 terabytes over the mission's lifetime. Assimilating and visualizing these data is a daunting task, even at this early stage, for computer and planetary scientists.

Most planetary data are maintained and distributed through NASA's Planetary Data Systems (PDS http://pds.jpl.nasa.gov). The tools to integrate these different data types (*e.g.,* Figure 1), in a coherent and productive way for scientific research, are often outdated or insufficient. The structure of planetary missions is such that different teams, each headed by a Principle Investigator, are responsible for the delivery of data associated with a particular instrument. For historical reasons, until recently, different data sets have been reported using different coordinate systems for Mars (for the interested reader, this seemingly peculiar approach actually reflects improvements in our knowledge of the spin rate of Mars, which plays directly into our ability to define accurately a spatial coordinate system for the planet's surface). For example, an impact crater seen in a Viking image of Mars may have a location assigned to it that is displaced up to a few tens of kilometers from the location assigned to the same crater in the topography data set. This makes overlaying an image on topography non-trivial since it requires either interactive adjustment of the two data sets or quantitative mapping to translate one coordinate system into another.

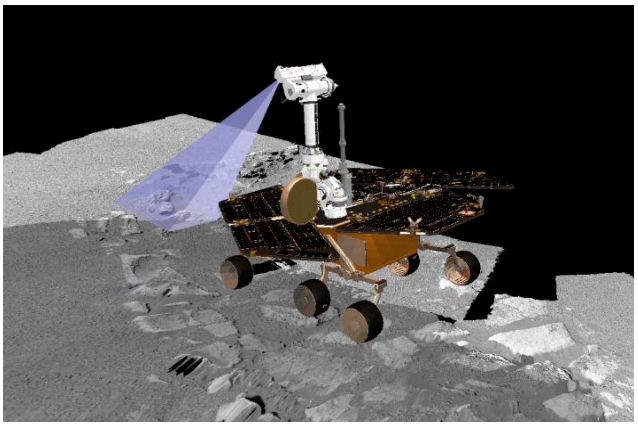

Figure 2a: Computer-generated visualization tool used by Mars Exploration Rover Opportunity scientists to find the rover's best position for observing a future target dubbed "Last Chance." Image Credit: NASA/JPL/Ames/Dan Maas. (Image: http://photojournal.jpl.nasa.gov/catalog/PIA05461).

Planetary scientists are exploring increasingly smaller and more localized regions, with areas as small as that covered by the MER Microscopic Imager (MI) (each MI frame covers a patch of ground 3 x 3 cm, with each data sample covering just 3 micrometers). Easy co-location of these small-scale data with multiple overarching data sets is essential to the scientific discovery process. Software applications need to interpret and combine the different scales of data for scientific research and tangible logistics, including correctly programming the Landers to land in the target region and to effectively explore the nearby terrain (Figures 2a-c). As Navigation team chief Louis D'Amario stated, the precision needed for the MER landings was equivalent to "threading a needle from 25 kilometers away" (http://marsrovers.jpl.nasa.gov/spotlight/navTarget01.html). Inaccurate data geo-referencing needs to be eliminated from the inherent difficult task of navigating rovers and deploying their instruments onto desired targets.

Currently, visualization of multiple data sets of Mars is done only as needed, and no standardized, affordable, and interactive visualization exploration tools exist. Integration of diverse data sets and the ability to quickly incorporate new data as they come on line is absolutely essential to understanding the geological evolution of Mars. Assessing the relative contributions of, and the interplay among, volcanic, tectonic, and climatic processes is critical to understanding the MER landing sites [see review in Cabrol *et al.,* 2003]. Here, we identify key tools required to advance planetary studies, and we initiate the design and distribution of visualization tools specific to planetary research, with a focus that the end products be platform-independent and rely on freeware so that the number of scientists that can help in the development and testing of the result is unlimited.

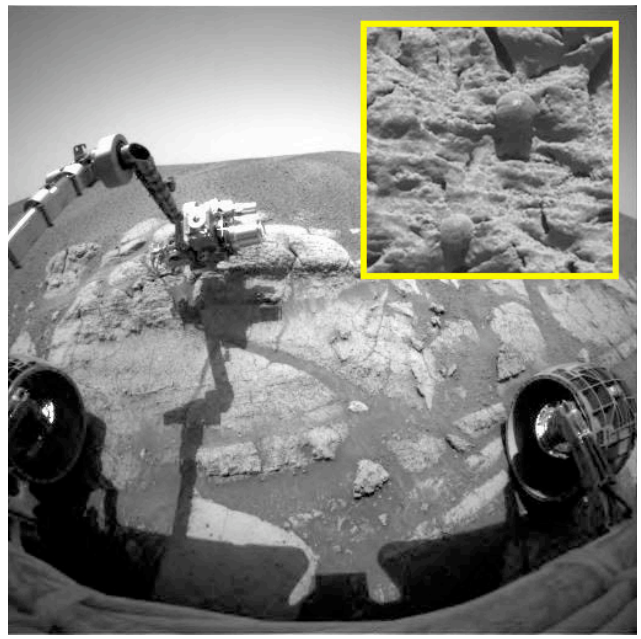

Figure 2b: The Rover Opportunity deployed its robotic arm also known as the Instrument Deployment Device on the El Capitan site. The inset image is from the Microscopic Imager (MI). Knowing the exact location of the MI image requires knowledge of the rover's kinematics state at the time of acquisition.

2. Visualization Tools Specific to Planetary Research

Planetary data set visualization is currently restricted to small-scale efforts by individuals, or larger, but not easily transferable, efforts by major organizations such as the Jet Propulsion Laboratory (JPL) or the United States Geological Survey (USGS). While the tools that have been developed for planetary research have been sufficient for rudimentary analyses (*e.g.,* Geographic Information System (GIS) utilities such as the USGS' Planetary Interactive GIS-on-the-Web Analyzable Database (PIGWAD) http://webgis.wr.usgs.gov), and products such as landing site visualizations are visually appealing (*e.g.,* http://marsoweb.nas.nasa.gov/landingsites). Yet, these typically have one or more of the following limitations: (1) allowable juxtaposition of data sets is often restricted to small pre-selected data subsets; (2) static products lack detailed geographical information, making them difficult to include in future work and of limited use in real scientific research; or (3) dynamic visualizations use simulated data or "artists' renditions", rather than real data (see Figure 2a). Moreover, a bundled suite of tools for the study of planetary data that every scientist can afford and easily use does not exist. Many existing products have limited interactive measurement tools and lack sophisticated 3D visualization capabilities, as well as poor ability to move easily from global to local scale visualizations.

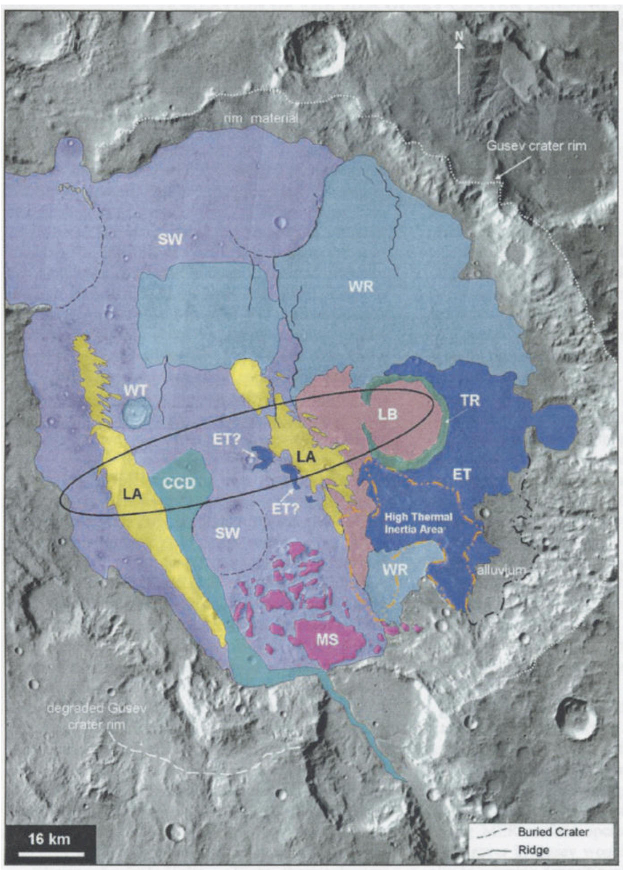

Figure 2c: Thermophysical unit map for Gusev Crater [Milam et al., 2003] in which colors essentially represent different geological units at the surface. For example, the yellow unit "LA" is thought to represent areas covered by sand dunes. The edges of this unit appear to have changed over the past 25 years, based on comparisons of images taken by the Viking Orbiters and those taken by the Mars Orbiter Camera onboard the MGS orbiter. The scientific community debated whether the areas denoted by blue and purple colors are covered by the kinds of sediments and boulders that are found in dry lakebeds on Earth. The proposed landing site of MER rover Spirit (black ellipse) was chosen specifically to allow exploration of a multitude of geologic rock types.

We strive to improve and extend these tools to include extensive geo-referencing of each data component and incorporation of interactive visualizations that take advantage of existing technologies, but are developed in a way that can be portable to new visualization technology as they come online (Figure 3). Our goal is to create modular tools that can take advantage of existing and future computer technologies.

We favor three main visualization strategies pivotal in conducting our current research. These strategies allow us to develop tools specific to our needs that can be distributed for use in future research. Each of these tools has, or will have, the ability to parallelize the processing across multiple nodes and maintain geo-referencing coordinates for future juxtaposition of new data.

Figure 3. High-resolution scalable tiled displays (GeoWall 2) provide scientists an environment for collaborative exploration of Mars panoramic images.

The first tool requires use of the commercial software 'Fledermaus' developed by Interactive Visualization Systems (IVS), (http://www.ivs.unb.ca/products/fledermaus/). Using Fledermaus we develop multiple 'scene' files that are a compilation of one or more data objects (for example, topography, imagery draped on digital elevation maps, or point measurements color-coded to represent various parameter values). The reference system can be spherical or cartesian (Figure 4). Fledermaus includes multiple capabilities (*e.g.,* accessing GIS formats) that are ideal for building 3D terrain models for planetary applications. Fledermaus and its resulting scene files facilitate the easy exchange of data and results between geographically distant scientists. Although Fledermaus is not freeware, it does have an associated freeware package 'iview3D' (http://www.ivs.unb.ca/products/iview3d/) that runs on multiple platforms (including Windows, Mac OS X, SGI, SUN, and Linux).

Fledermaus and iview3D can display a scene file and an accompanied flight path movie file, which on execution sets up an automated flight path through the data. This allows a researcher to record the location of an interesting feature or phenomenon for repeated replay. Sharing data as interactive 3D scene files is the preferred method of sharing observations and results that cannot be effectively communicated using the highest resolution 2D static images. The Fledermaus software allows for exporting these large datasets as QuickTime movies, which do not require sophisticated computer hardware for viewing (http://www.siovizcenter.ucsd.edu/streaming/index.html).

Our second visualization strategy involves combining different data sets with draggers and manipulator widgets available in the Open Inventor library (http://oss.sgi.com/projects/inventor/), which is an object-oriented 3D toolkit. The Coin graphics library is a free implementation of the Open Inventor library developed by Systems in Motion (http://www.coin3d.org/) that we used to port these visualizations to different operating systems. On top of the base functionality of SGI's OpenInventor, Coin provides well tested cross-platform support, POSIX threading, 3D sound, embedding of movies and 3D texture, and with the addition of Volumizer, for volume rendering. We use the interactive viewer "ivview", which is an Open Inventor program, extensively to view the Mars data.

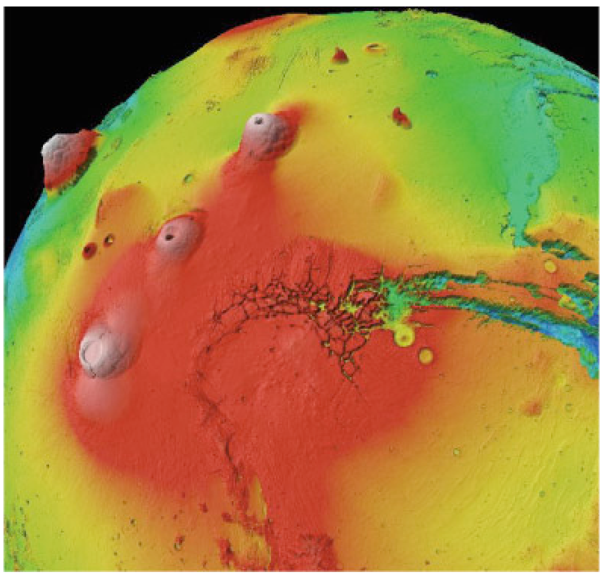

Figure 4. Viewing data in different geometries highlights different features in the data. The spatial scale of features on Mars such as the volcano Olympus Mons and the 4000km-long canyon Valles Marineris is such that representation of the topography of these features using a flat Cartesian geometry, rather than spherical geometry, is misleading.

The third visualization tool, called 'Juxtaview', is currently under development at the Electronic Visualization Laboratory, University of Illinois at Chicago (http://www.evl.uic.edu/cavern/optiputer/juxtaview.html). Using Juxtaview, high-resolution panoramic images captured by the Mars Rovers Spirit and Opportunity can be used to browse through considerably large 2D images on large-scale high-resolution displays. The Juxtaview program parses through data sets resident on each graphics cluster node and puts a subset of the large image into memory for display. The current version of this software can be used to interact with an image as large as 14 gigabytes (24Kx24Kx24Bit) on a cluster of 64-bit processors, well beyond a regular workstation's capabilities of ~2GB size images (6Kx6Kx24Bit) with a viewing area of up to 1920 by 1200 on standard LCD displays.

3. Data exploration using multiple display platforms

The Scripps Institution of Oceanography's Visualization Center (http://www.siovizcenter.ucsd.edu/) operates a variety of scalable resolution and stereoscopic visualization systems. Each system has its own unique capabilities that support scientific research efforts and enhance the viewer's overall experience. Two systems housed in this center are particularly helpful in our scientific research, and we foresee their extensions will greatly enhancing future planetary research. The first is the level-0 OptIPuter, which is a high-resolution cluster-driven tiled display system. (This system is an IA-32 cluster computer, with 10 nodes of dual Intel Xeon 2.4 GHz processors with NVIDIA Quadro 2000 FX graphics cards.) Eight nodes are responsible for driving the viewing screen (2 IBM T221 22.2" TFT LCD), providing a resolution of 3840 x 2400 pixels, that, when combined, results in a total resolution of about 18 million pixels (Figure 5).

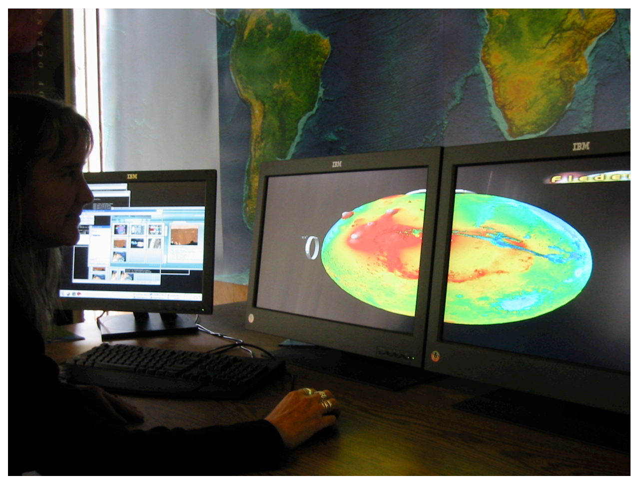

Figure 5: The Level-0 OptIPuter. Using a freeware viewer iView3d and the Mars 'scene' file from our publicly accessible visual object library (http://www.siovizcenter.ucsd.edu/library/objects/index.php), scientists can interactively explore the topography of Mars or explore smaller subsets of the data on other more primitive desktop systems (multiple platforms supported).

The high-resolution displays and computing power of the level-0 OptIPuter extends the scientist's workstation by increasing the number of pixels and its processing speed. For example, the interactive data set depicting the topography of Mars can be displayed on the tiled displays using the freeware iView3D and freeware Chromium [Humphreys *et al.,* 2002], or high-resolution panoramic images sent by Mars Rovers Spirit and Opportunity can be viewed with 'Juxtaview'.

The second viewing system optimal for planetary research and planning future planetary missions is the large scale Highly Immersive Visualization Environment (HIVE), which consists of a 3.2 mega-pixel Panoram® GVR-120E curved floor-to-ceiling screen (8'6" x 28'4") driven by the SGI ONYX 3400 graphics 16 MIPS processor supercomputer with 16 GB addressable memory [Kilb *et al.,* 2003]. The system is equipped with transmitters and LCD shutter glasses that permit stereographic 3D viewing (1,966,080 stereo-pixels per eye). The HIVE provides a theatre-like setting for a group of scientists to be immersed in their data and together interactively explore and identify key features (Figure 5).

We can't stress enough how important it is to bring together groups of scientists in a place where they can all view and discuss the same data. Crowding around a standard LCD display is okay for some tasks, but when the datasets involved span multiple orders of magnitude and rely on multiple sub-areas of expertise, large scale viewing capabilities is preferable (Figure 6). Larger scale settings allow researchers to rapidly digest huge volumes of data and come to conclusions that might not otherwise be obvious. This need is so pervasive with missions like MER that in one planning room, there were 7 HDTV projection systems driven off of 4 workstations. These screens covered all of the available wall space and displayed a variety of information including 3D animations, full resolution mosaics, command sequence planning diagrams, thermal, bandwidth, and power budgets, and scheduling plans.

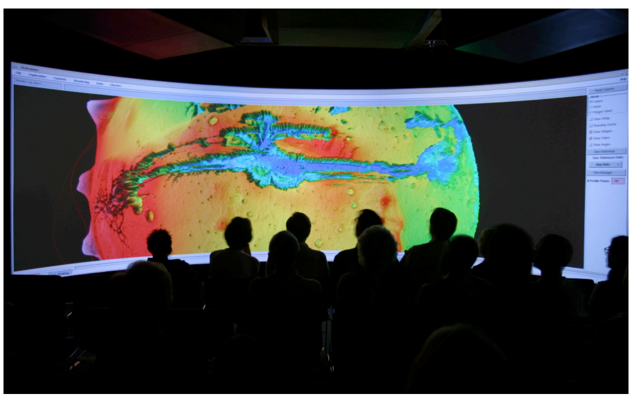

Figure 6: The Scripps Institution of Oceanography (SIO) highly immersive visualization environment (HIVE). A group of visitors in the SIO Visualization Center view the topography of Mars. This large-scale display and powerful computer systems are optimal for groups of scientists to hold discussions and planning sessions.

4. Applications to Planetary Research

Future Mars missions, such as the extensive Mars Science Laboratory planned for the 2009 lander, will draw heavily on what we learn from the data collected from the Spirit and Opportunity lander missions. We next identify types of visualization tools that play a major role in helping researchers understand current data sets, and aid in future mission planning along with public education and outreach. These three primary visualization tools allow exploration of multiple datasets, and can help planning teams pinpoint future study regions. In combination, these types of tools form the groundwork for what we have identified as those most likely to be useful in future planetary research.

4.1 3-D Visualizations of the topography of Mars

Our first application example focuses on interactive 3-D renditions of the topography of Mars [Smith et al., 2001]. Currently, we know the topography of Mars better than we know the topography of Earth. Unlike Earth, the surface of Mars is not hidden below large oceans that mask the seafloor below, allowing the topography to be accurately determined by the Mars Orbiter Laser Altimeter (MOLA) instrument. MOLA sends out laser pulses that bounce off the planet's surface. The two-way (spacecraft-ground-spacecraft) travel time of a pulse signal is measured, and, by using the frequency and speed of the signal, an estimate of the height of the spacecraft above the Martian surface can be determined and in turn the topography or surface elevation. This method allows us to calculate the topography of Mars to an accuracy of a few meters, two to three orders of magnitude better than the accuracy of previous data from the 1975-1976 Viking missions.

In general, 3-D interactive capabilities with the MOLA data allow identification of the many features that are easily missed in static images. Interactive adjustment of vertical exaggeration permits detailed examination of slump features, crater wall structure, and other geological features. Understanding these features helps scientists sculpt hypotheses about the geological evolution of individual regions and of the evolution of the planet as a whole.

We use MOLA-derived topography data grids and the Fledermaus package to develop interactive scene files to explore the entire high-resolution topography of Mars. Previously, topography exploration was limited to data reduced to only data sub-sections, restrained by computer memory and storage limitations. We create OpenInventor models of the global MOLA topography (spherical geometry) using one of the lower resolution MOLA grids using standard linear decimation techniques (e.g. using GMT grdsample). The topography in areas of detailed interest, *e.g.,* MER landing sites, is replaced regionally with the highest resolution MOLA grid.

At a regional or local scale we generate a terrain model from the MOLA topography that can be displayed with the freeware multiplatform visualization tool "ivview". Spatial referencing and elevation information are preserved. Level-of-Detail visualizations can be generated using the Open Inventor LOD node in which the level of detail seen in the 3-D image depends on the viewer's distance from points on the surface. As one "flies over" the topography, the level of detail is dynamically adjusted (Figure 7). We expect this now relatively standard technique of level-of-detail modulation to be key in future planetary studies.

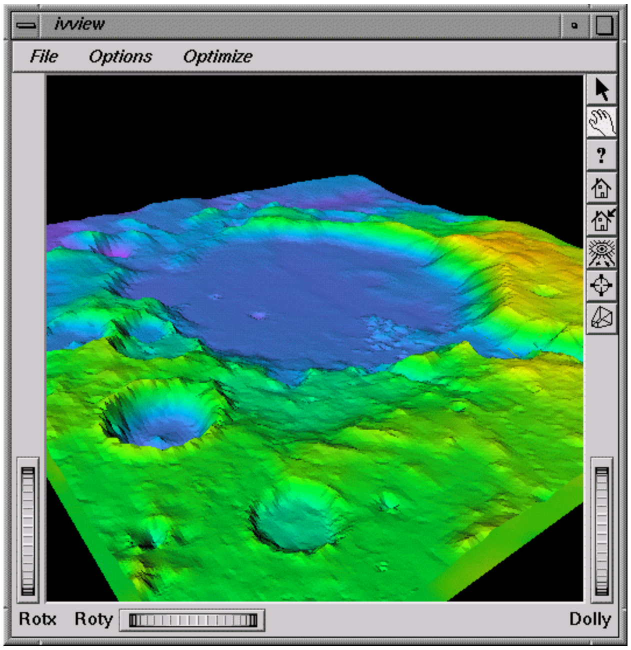

Figure 7: 3-D rendition of MOLA topography for Gusev Crater on Mars, which was the site of the MER Spirit. More detail is seen in the foreground, closest to the viewer, whereas more distant regions in the background are rendered in lower resolution.

4.2 Interactive Tools for Overlaying Data Sets

The ability to overlay multiple data sets is critical to geoscientific research projects. For example, understanding whether standing water persisted in Gusev crater requires us to be able to quantify the spatial correlations of low topography (altimetry data at the orbiter scale), the presence of hydrous minerals (spectrometer data at the lander and orbiter scale), visual evidence in imagery of erosion and deposition (images at lander and orbiter scale), and the thermal characteristics of rock types present (thermal emissivity data at the lander and orbiter scale).

Here, we use Mars Orbiter Camera (MOC) and MOLA data for Gusev Crater, which was the landing site of MER's Spirit (Figure 7). MOC and MOLA data, are, in theory, easily aligned using the geographical information contained in the data file headers. However, these data sets were created using different reference surfaces for Mars due to modifications of the spin rate of Mars that dictates the spatial coordinate frame of reference. A detailed, quantitative co-registration approach has been designed by Anderson *et al.* [2003] and applied to the MER landing sites.

The approach, while powerful, is time consuming. Alternatively, 3-D draggers (basic widgets used for data or image manipulation) in the Open Inventor library can be used to manually adjust the placement of MOC images on MOLA (or any other base map, *e.g.,* Viking context image). This approach retains real-world x, y, z (longitude, latitude, elevation) information, so that the adjusted center position for a MOC image is easily obtainable. Our approach to align the MOC image and the topography is advantageous for small numbers of images and for exploring the visual correlations of features between data sets.

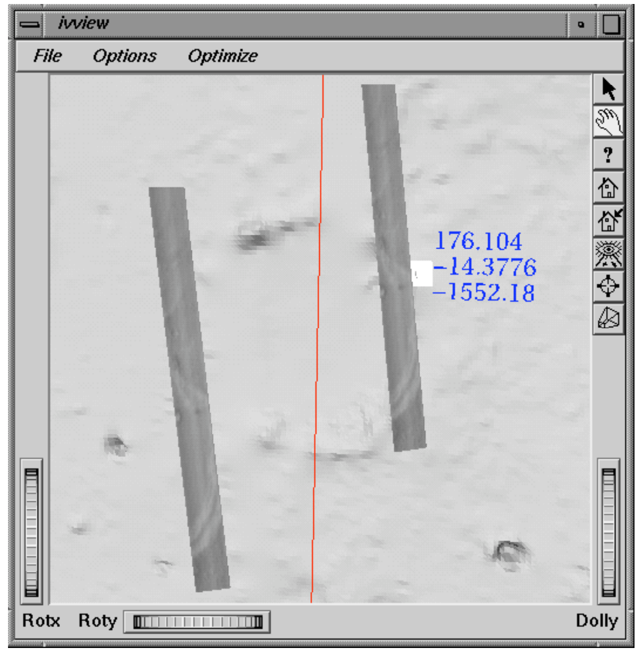

Figure 8: MOC image (approximately vertical grey swatch) placed on topography using the geographical information contained in the MOC header (a different reference system from the topography data set). The 3-D dragger allows the image to be moved, to yield visual alignment of the crater rim observed in the MOC image with the topographic rim. The revised image center (latitude and longitude) are automatically computed and output to the user.

4.3 Stratigraphic Models of Gusev Crater from an Isosurface Visualization Tool

Understanding the setting of current Mars landing sites is critical to unraveling the geological history of Mars, in particular the role that water (either sub-surface or surface) may have played in shaping Mars' present landscape. We use a movable isosurface to simulate water level changes on Mars to help identify the lowlands that potentially had water in the past and therefore are prime spots for exploration. In a simplified example, we apply these flooding models to Gusev Crater, which is the site of the MER Spirit lander. We begin by overlaying the thermophysical map of Milam *et al*. [2003] (see Figure 2) as a texture map on the topographic terrain model. We simulate the water level using as a flat plane that can be raised or lowered to predict stratigraphic history models (Figures 9a-b).

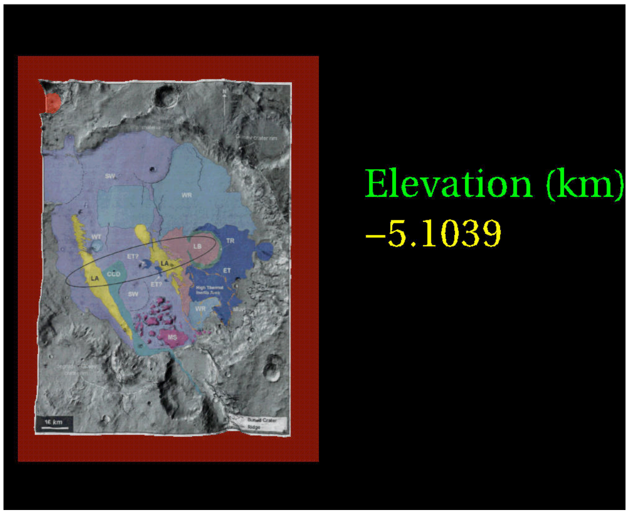

Figure 9a: Flooding sequence of Gusev Crater. Thermophysical unit map in Figure 2c is juxtaposed with an isosurface (red) representing water level. The water level can be interactively adjusted with the dragger to easily discern regions of lowest elevation, which are prime locations to potentially find evidence of water. Water level in real world (Mars) altitude is continuously updated on the screen during interactive water level adjustment.

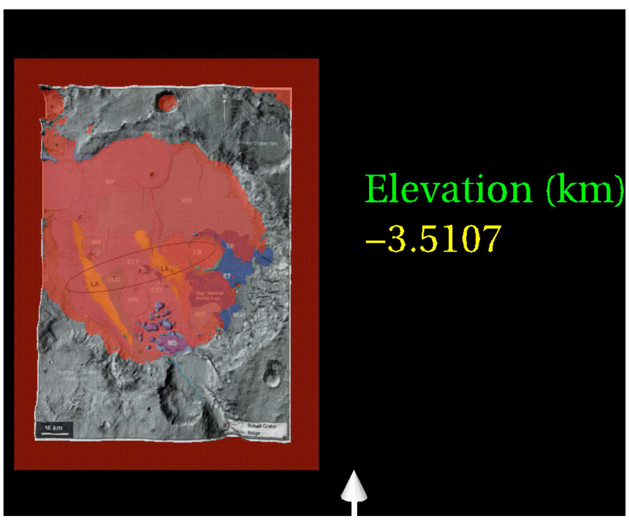

Figure 9b: As in Figure 8a but with an increased water level, indicating that the base of the full crater is not of uniform depth (i.e., portion in lower right corner remains above the water depth).

5. Major Results and Findings

The visualization tools we present here were developed to help test a small subset of MER data for reformulating existing hypotheses and identifying key tools needed for future planetary research and data archival. This focus on quantitative, interactive, 3-D visualizations of recently acquired planetary data allows the following: (1) testing of geological theories such as the popular hypothesis that the MER landing site, Gusev Crater, was once the site of an ancient lakebed; (2) efficient evaluation of data streams and data quality through interactive adjustment of overlaid data sets, essential for proper alignment of data from different reference systems; (3) streamlining the capability to move from the global (orbiter) to the local (lander) scale; and (4) the production of a series of interactive and semi-interactive Mars data visualizations, useful for research and formal and informal education.

Through the experience we have gained using these Mars orbiter and Mars lander data to test various visualization tools, we find the main challenges in integrating available data into useful tools for research and education include:

(1) Accounting for the variable spatial/temporal data coverage and spatial resolution of the data that can span 7 or more orders of magnitude.
(2) Using multiple types of archival data formats (spherical harmonic models, multi-spectral cubes, individual orbit passes).
(3) Efficiently pre-processing the data into a useable format.
(4) Visualizing data volumes with the ability to change the transparency to highlight features of interest.
(5) Unraveling different coordinate systems within data subsets, which is difficult for planetary research because the base datum changes with time.
(6) Maintaining a history of the data acquisition and processing so that quality assurance is testable in the future.

These challenges indicate the need for significant "user expertise" to ensure that nuances about each data set are understood – for example, a planetary elevation data set in spherical coordinates is quite different from camera images, or from magnetic field measurements evaluated at individual points. The ability to easily flip from one domain to another is currently beyond our grasp, at least for many planetary data, because the coordinate transformations required to geo-reference even basic data is not yet accurately in place.

6. Future Directions

It is clear that collaboration is needed between geoscientists and computer scientists to efficiently assimilate and study the large quantities of planetary data that will come on line in the near future. The increasing support for interdisciplinary studies by funding agencies such as the National Science Foundation (NSF) and the individual cross-discipline links being established between the two fields indicate that other researchers share this vision.

The vast amount of planetary data being collected will require multiple machines, possibly in different locations, to keep up with the data processing and archival requirements. Spatially distant multiprocessing can make use of the larger machines that have larger memory storage, while simultaneously capturing the compute power of the smaller more abundant machines (Smarr *et al.,* 2003). To effectively harness these resources, key software tools need to be identified and written in modular ways for reuse on changing computer architectures and operating system technology. Through this work we find the key tools in planetary research include moveable surfaces (e.g., to simulate flooding), juxtaposition and accurate geo-referencing of different data types, interactivity with the data to obtain collection statistics or value and error specifics, the ability to view considerably large 2D images on large-scale high-resolution displays, and Level-of-Detail visualizations to best explore datasets that span multiple dimensions (millimeter to 1000 of kilometers).

In summary, our future efforts to unify, create and use tools for planetary research that can be used now and in the future include:

(1) Continuation of visual object development of MER and other Mars related data and research to distill the large collections of data expected to be assembled within the next few years.
(2) Continued distribution of visual objects through a web-accessible library (http://www.siovizcenter.ucsd.edu/library/objects/index.php) that can be quickly downloaded and assembled into 3D models. In this manner, investigators can incorporate their data into our products without having to start at "square one".
(3) Continued collaborations with Earth Science Departments that have specific resources set aside for Geosciences visualizations and departments that are currently planning larger high-end theaters to test the portability of our data products.
(4) Generation of QuickTime movies (static and VR) with resultant file sizes small enough to be viewed on low-end computer systems but for which the original data size is so substantial that movie production is possible only on our high-end system (http://siovizcenter.ucsd.edu/library.html).
(5) Continued efforts to link together computer science and geoscience specialists to assure that the visualization tools needed for planetary study are modular enough to accommodate changes in technology.

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