ADVISER: Immersive Scientific Visualization Applied to Mars Research and Exploration

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Abstract

Geologists explore the Earth at specific surface locations and then integrate these data using more synoptic approaches. Planetary geoscientists, however, are forced by the nature of the available data to start from synoptic and orbital data and work down toward the surface. We describe Advanced Visualization in Solar System Exploration and Research (ADVISER), a problem-solving environment that uses advanced visualization techniques to bridge an important gap between the cartographic data sets derived by remote sensing and their application in geoscientific research. ADVISER integrates and extends state-of-the-art hardware and software technologies into a set of tools that provide the planetary geoscientist with the capability to operate and analyze data and to undertake mapping as if they were on or near the surface of a planet. Application of these tools (e.g., virtual field tools and notebook) to analysis of the north polar-layered terrain on Mars provides insight into polar cap formation and evolution and mission planning activities.

Introduction and Background

Geologists explore the Earth primarily through fieldwork and analysis of the geological record at various points on the surface. They then integrate these individual points of understanding through more synoptic analyses often aided by the integrating perspectives seen from image and topographic data acquired from aircraft and Earth orbit.

Planetary geoscientists commonly work toward an understanding in the reverse order. The distances and times involved dictate that the first data from individual moons and planets comes from flybys and orbital spacecraft, perhaps in some cases evolving toward the deployment of a few landers and rovers, and for the Moon, human explorers. Now that global data sets are available for the Moon, Mars, and Venus, we can begin to undertake the detailed exploration of planetary surfaces that is required for the full understanding of the evolution of planets (e.g., Head, 2001).

How do we accomplish this? In only a very few cases can we expend the resources to put a lander and rover, and thus our eyes and ears, down onto the surfaces of the planets. The successful Pathfinder rover (e.g., Golombek *et al.*, 1999) and the currently operating Mars Exploration Rovers (e.g., Squyres *et al.*, 2004a, 2004b) are testimony to the exciting results that can be obtained by such surface exploration. Fortunately, developments in advanced visualization and immersive virtual reality environments have created the ability to place the geoscientist back down on and near the surface to visit virtually any part of the planet they wish to see, and to regain the perspective that is the foundation for the understanding of the geological relationships necessary to unlock the record of the history of the planets. Specifically, we are using a Cave Automatic Virtual Environment (CAVE) fully immersive virtual reality system (Cruz *et al.*, 1993) to put geoscientists in remote places such as Mars. Our CAVE's construction physically consists of four 8-foot square display surfaces that have edges seamlessly joined to form a cube-like volume. We have a front wall, a left wall, a right wall, and a floor surface (Figure 1). Computer-generated stereo images are projected by one computer per wall using an Electrohome 9500 projector. Our four-node cluster has one nVidia Quadro FX 3000G graphics card per computing machine. All of these components are synchronized to present to one or more viewers a virtual environment of Mars that is generated from various data sources (e.g., topography and remote sensing data).

Image and altimetry data, as well as associated data sets describing the physical and mineralogical properties of the surface materials, are now available for Mars (and, to a lesser extent, for other planetary bodies), and a substantial amount of effort has been invested in putting these data sets in map form and placing them in a common cartographic coordinate system, an essential step before they can be used comparatively. Aspects of this process of photogrammetric/cartographic analysis of Mars remote sensing data are described in several other papers in this special issue of PE & RS. Even with the key data sets available in common cartographic coordinates, however, extracting the maximum geoscientific insight from them is a challenging task that depends critically on having the right software tools.

What is required to overcome this major barrier to the exploitation of planetary photogrammetry and remote sensing data? Clearly, a set of tools that can both ingest data sets from multiple missions and present them to the user in the most effective way are required. Unfortunately, much of the planetary science community is not aware of the computer science and technology developments that can enable

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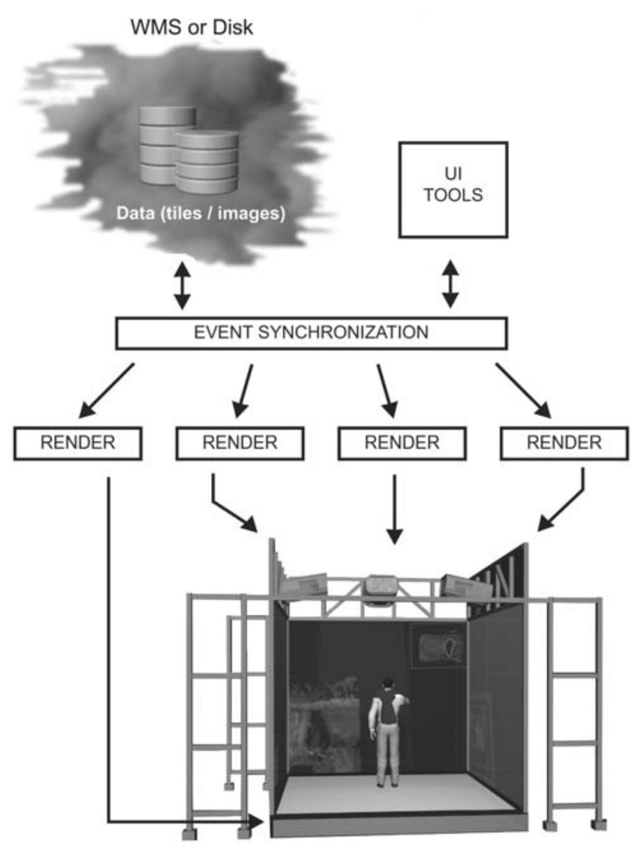

Figure 1. ADVISER system components and the CAVE immersive virtual reality system. See text for detailed explanation.

interactive virtual exploration, and thus do not seek to use them in their research and teaching. For the past several years, scientists in the Planetary Geosciences Group have been working with personnel in the Center for Computation and Visualization (CCV) and Department of Computer Science at Brown University to explore, develop, and publicize capabilities in the planetary geosciences. These capabilities have come in two areas: (1) Advanced visualization techniques, and (2) Immersive virtual reality. In the past, high-resolution terrain visualization and other forms of planetary data visualization have taken separate paths. High-resolution 3D representations of terrain data have typically been computed off-line as fixed sequence movies, while at the same time planetary data sets are commonly presented for query in mapping format (the Planetary Data System Map-A-Planet and the USGS Astrogeology Branch PIGWAD site). Less effort has gone into integration of planetary data sets and recent developments in visualization that can provide real-time interactive visualization of high-resolution data and analysis techniques that facilitate the exploration and exploitation of the data.

Therefore, we see the demonstration of this synergism as a fundamental first step in establishing the importance of these techniques so that they can be developed further and be routinely applied to scientific problems in research throughout the community. Here we describe these techniques and tools for photogrammetry applied to address several remote sensing data sets to important scientific problems in geologic mapping and analysis on Mars.

Approaches and Related Work

Our contribution is in the development of an immersive tool for planetary geoscientists. In particular, we are advancing the state of the art in user interfaces and rendering techniques as driven by the specific science problems described later, and as much as possible, leveraging the other necessary components including data formats, data repositories, and data management. Approaches that employ off-line rendering are not applicable to our current work because interactivity (i.e., rendering 30+ frames per second) is a requirement for ADVISER, though past work of this type does illustrate some of the benefits of terrain visualization for planetary geology (e.g., Kirk *et al.*, 1992; Chapman *et al.*, 1994). An existing resource whose objectives resemble those of ADVISER is the NASA Ames Marsoweb (Deardorff *et al.*, 2002), which offers interactive map display and 3D visualization of Mars data sets from multiple missions and instruments. The Virtual Reality Markup Language (VRML) visualizations that this site provides over the Internet are non-immersive, however, and fall short of the performance needed for virtual field geology.

Data Sources

There are several technologies for managing and analyzing planetary geosciences data. The Mars Express Geosciences Information System (MEGIS) (Ori, 2004) focuses on providing data management and analysis tools for the ESA Mars Express mission; however, it was developed using the available data from the NASA Viking, Mars Global Surveyor (MGS) and Odyssey missions. The NASA Planetary Data System is a distributed data archive; it provides a simple web front-end (Garcia, 2005) to select, customize and download maps for a variety of planetary bodies, including Mars. There are also data manipulation tools for specific mission instruments; for example, Arizona State University provides tools and a clearinghouse for MGS data (Planetary Image Research Laboratory, 2005); USGS provides the excellent image processing toolkit ISIS (ISIS Development Team, 2005). There are additional efforts that focus on public outreach and education. We are also using ArcGIS® for compiling data from the above mentioned sources.

3D Visualization Tools

Immersive Planetary Exploration

There are prior examples of the use of Immersive Virtual Reality (IVR) and semi-immersive VR visualization in planetary exploration. In early work at NASA Ames, McGreevy (1993) combined geometric rendering of terrains with image-based rendering (IBR) techniques to provide interactive performance with the limited rendering capabilities of the day. McGreevy (1993) presents a review of VR techniques and applications to several NASA missions. Recognizing the limitations of studying spatial data with a "desktop metaphor" he encourages the use of an "exploration metaphor" for improving the operational effectiveness of terrain exploration. The Virtual Planetary Exploration (VPE) system featured a Head Mounted Display and used relatively modest graphics hardware to present stereo images to the user. Graphics hardware has improved by orders of magnitude since then, and coupled with better algorithms, we are in a position to present topographic details to the user at much higher resolutions. A more recent project, the "GeoWall" (Morin *et al.*, 2001) is a successful example of the application of low-cost virtual reality technology to geosciences research and education. The hardware setup typically consists of a single wall display and a couple of projectors in a passive stereo configuration. A single computer machine is used to drive the projectors. A variety of free 2D (standard image viewers and video players) and 3D software such as Immersaview (Spale, 2004), Vis5D (Hibbard and Santek, 1990), Walkabout (Johnson, 2004), and Wiggleview (Nayak *et al.*, 2005) are used for scientific visualization. The hardware components of GeoWall could be useful for our outreach and education needs, but the software does not provide the high performance our research needs.

Interactive Terrain Visualization

A variety of terrain visualization software (both commercial and research) is currently available (Discoe, 2002), but no single package could meet all of ADVISER's requirements. For example, MOLA data for the entire planet is available at a resolution of 46k × 22k, which produces approximately two billion triangles. Among the few candidates that satisfy our performance criteria, we have found that ROAM is the most promising (Duchaineau *et al.*, 1997). This system supports out-of-core paging of data and a view-dependent simplification algorithm to render the visible terrain at full resolution. Recent improvements to the algorithm (Duchaineau, 2003) use programmable features of commodity graphics hardware and texture paging. Additionally, ROAM can also support high-resolution insets of both altimetry and texture.

Among other candidates, the SOAR algorithm (Lindstrom and Pascucci, 2001) is also promising with demonstrated interactive performance for 16k × 16k terrains. VTP software (Discoe, 2002) presents a range of features and visualization algorithms; unfortunately, its performance does not scale to terrains larger than 8k × 8k.

Immersive Multi-variable Visualization

Vis5D (Hibbard and Santek, 1990) is designed for interactive visualization of large gridded data (e.g., numerical weather models). The user can create isosurfaces, contour line slices, colored slices, volume renderings, and other visual structures and interactively view them in real time. One can trace wind trajectories, make text annotations, and do interactive data analysis. The Visualization ToolKit (Schroeder *et al.*, 2004) is a library of visualization tools that can be applied to ADVISER for vector field visualization. Neither toolkit supports high performance terrain and texture rendering of very large data sets. However, we do plan on using components of them for some scientific visualization requirements of ADVISER.

The ADVISER Problem Solving Environment

We are working to accomplish our geologic analysis goals through ADVISER, a problem-solving environment (PSE) for planetary geosciences. We define the PSE as a toolkit: a set of tools that provides the planetary geoscientist with the capability to explore and analyze data as if they were on or near the surface of a planet. Below we describe ADVISER's components, the technical challenges in building the system, and our current implementation.

ADVISER Scope

The ADVISER PSE has five basic parts:

(1) ***Geoscientist on the Surface.*** This enables planetary geoscientists to be on or near the surface by means of immersive virtual reality, such as the CAVE (Figures 1 and 2). The large volume of high-resolution data required also places severe requirements on system performance.

(2) ***Importation and Visualization of Multiple Data Sets.*** One of the basic components is on-demand importation, co-registration and overlay of relevant image format data sets to enhance the eyes of the geoscientists and their ability to correlate and interpret data for scientific analysis. For example, in Figure 2 geoscientists are exploring the north polar cap of Mars (seen in the background of Figure 2a through d), using topography from the Mars Orbiter Laser Altimeter, with Viking Orbiter images overlain (Figure 3a and b) and Mars Orbiter Camera (MOC) very high-resolution images (Figure 3c) inserted into the scene. Other high-resolution data sets that we utilize include THermal EMission Imaging System (THEMIS), High Resolution Stereo Camera (HRSC), OMEGA Imaging Spectrometer, synoptic Gamma Ray Spectrometer (GRS), Thermal Emission Spectrometer (TES), and other types of derived regional data sets (slope, mineralogy and temperature).

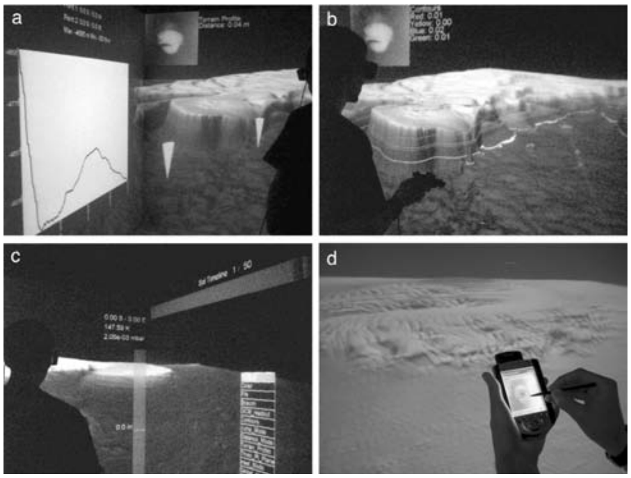

Figure 2. Views inside the CAVE showing IVR portrayals of the Mars North polar cap and various tools associated with ADVISER implementation. (a) Topography and altimetry profiles. (b) Topographic contours and tracing of layers in the polar layered terrain. (c) Data displayed from the NASA Ames atmospheric general circulation model (GCM) (e.g., temperature, pressure, etc.). (d) A wireless PDA for use in instant navigation, data display and recording.

(3) ***Field Kit.*** This is analogous to the geologist's field kit and consists of a set of software functions that have the capabilities commonly carried out by the geologist in the field using tools like the Brunton compass (orientation, direction, slopes, strike and dip of strata), and altimeter. It consists of selectable items including such things as elevation of any point chosen, relative elevations, slope determinations, topographic and slope profiles, strike and dip of planes defined by several points on the surface (e.g., a continuous layer in the polar layered terrain or an outcrop in Valles Marineris), and the ability to determine wind directions and velocities. For example, in Figure 2a, two markers (downpointing cones) have been placed on the surface to determine the exact elevation of each point, and to assess the nature of the topography between the points. On the left wall, the elevation of the two end points and an altimetry profile between the two points are displayed. In Figure 2b, contour lines (lines of equal elevation) can be displayed at specified intervals (e.g., every hundred meters) or special contours can be highlighted and color-coded to trace the relationships of plane-like beds in the polar terrain to topography, and to determine their angular orientation (strike and dip). Atmospheric data can also be called up from the NASA Ames General Circulation Model (GCM). For example, in Figure 2c, data on local temperature and pressure are displayed as the scientist navigates across the polar cap. Also displayed on the right wall are time-lines that span a full Mars year for these values. In the lower right of Figure 2c is a menu from which many of these tools can be selected.

(4) ***Ancillary Virtual Field Instruments***. These are analogous to the additional tools that the geoscientist carries in the field, such as cameras, Global Positioning System (GPS),

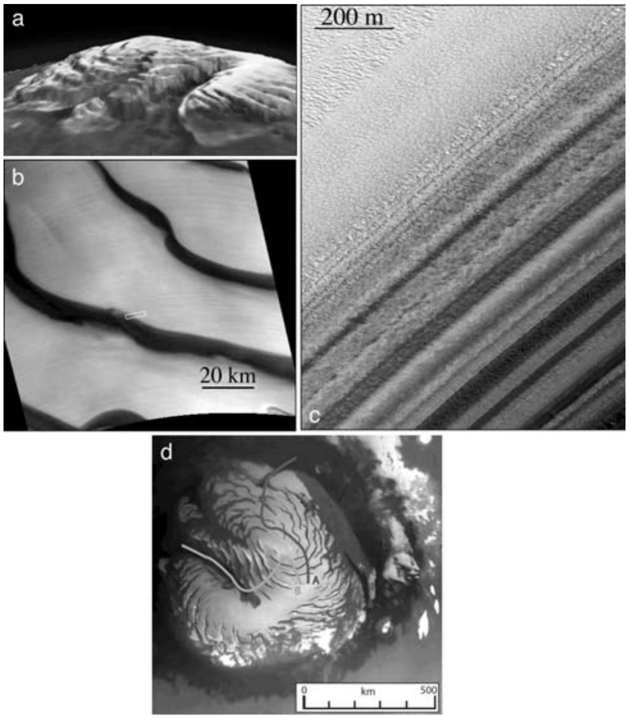

Figure 3. Data types for the exploration of the North polar cap. (a) Viking image data superposed on MOLA altimetry and viewed in perspective. (b) Viking image data showing troughs in which the polar layered terrain is exposed. (c) MOC very high-resolution data of the polar layered terrain. (d) Landing sites and traverses investigated in the Palmer Quest mission design study.

and field notebooks. Specifically, we are developing the capability for virtual photography, virtual GPS, and an electronic field notebook that will record all relevant observations and images in a downloadable integrated data set. For example, in the upper left of Figure 2b is seen the overview and location map that displays, not only the current location of the geoscientist, but also the previous locations and stations, and a traverse map indicating the terrain that has been navigated and investigated up to this point in the session. Preplanned traverses can also be inserted and followed using this tool. This active traverse map forms the basis for the field notebook and its data entries. We are also investigating the use of a wireless Personal Data Assistant (PDA) (Figure 2d) for automated click-and-go navigation and a variety of other user interface elements.

(5) ***Geologic Mapping***. Culminating the use of all of these tools is the compilation of a geologic map. Here we import geologic map data in common vector format(s) and display them along with other remote sensing data sets. We can create and edit geologic map information directly on the visualization and export the results to a digital geologic mapping environment.

System Description

The data, rendering, and user interface components of ADVISER are shown in Figure 1. While ADVISER will ultimately be able to run in multiple display environments, we show it driving a four-wall CAVE in this scenario. The four instances of the application (labeled "RENDER" in Figure 1) run in synchronized execution mode and together present the viewer with a seamless rendering of the 3D data across the display's walls. Each application instance generates the display for a single wall of the four-wall CAVE. Data can be imported from local disk or downloaded from the internet (e.g., using the Web Map Server standard). The user interface component supports basic navigation as well as the geologist's tools. Our implementation is written in C++ and OpenGL. Our approach to synchronizing multiple rendering nodes is described in Lemmerman and Forsberg (2004).

Current Implementation

We have built a prototype system that currently implements a major subset of the ADVISER capability. It renders stereo frames of detailed topography at 30+ frames-per-second (FPS) in our CAVE, supports high-resolution camera image overlays on topography, and a subset of the geologist's tools described above. A geoscientist can be immersed in a terrain that is about 8,192 samples square and interactively navigate through it (Figure 2). Our implementation uses an extended version of the ROAM system implemented at the Department of Energy Lawrence Livermore National Laboratory (Duchaineau *et al.*, 1997). ROAM efficiently implements the simple idea of rendering terrain near the viewer at highest detail and simplifying more distant terrain. ROAM's execution time is proportional to the number of underlying triangle changes per frame, which is typically a few percent of the rendered mesh size, hence ROAM performance is insensitive to the resolution and extent of the input terrain. Twenty sub-regions of MOLA data that collectively cover all of Mars as well as a region of Antarctica can be viewed. We have embedded MOC (Figure 3c), Viking, and HRSC images over the MOLA data (Figure 3a and b) enabling the scientist to study multiple images in their proper terrain context. Currently, we use standard OpenGL texture mapping to overlay images; this limits their resolution to 4096 × 4096 pixels.

The field kit currently supports a compass, an altimeter, a tool for producing a terrain profile between any two points, and strike and dip measurement capability (Figure 2a through c). For operations requiring elevation data we index into a 2D height field grid. For strike and dip plane calculations from three or more user-specified sample points we use the NAG singular value decomposition routine. Our implementation also has a basic mechanism for indexing into the Mars GCM data based on a time variable and user position. Using this we display GCM data such as atmospheric pressure and temperature at the viewer's location (Figure 2c).

Ancillary virtual field instruments include a heads-up-display map that provides overviews of the current location of the scientist (Figure 2a and b). Multiple contour lines derived from dynamic user-specified elevation values can also be applied to the terrain (Figure 2b). A custom pixel shader was integrated with ROAM to render the dynamic contour lines in real time.

Application to Current Problems in Planetary Geoscience

We are undertaking a three-pronged geosciences investigation to assess the history of atmospheric and subsurface volatiles on Mars and to demonstrate the scientific usefulness of visualization and IVR in planetary geosciences with the ADVISER system. ADVISER was used for all of these investigations thus far, but some results were made possible with conventional desktop and lab tools that in the future will be integrated with ADVISER. The three-part science approach builds on central research themes in planetary geoscience, as well as the basic NASA research and exploration theme "Follow the Water" for Mars. The basic themes are (a) Formation and evolution of the north polar cap, (b) Formation and evolution of tropical mountain glaciers, and (c) Automated and human exploration of Mars.

The North Polar Cap

Among the major questions associated with formation and evolution of the North polar cap are: (a) the age of the cap (Figure 3a), (b) the origin of the swirl-like troughs in the cap (Figure 3b), (c) the nature and origin of the layers exposed in the troughs (Figure 3c), and (d) the lateral extent of the cap. In related research, we have interpreted a range of geological observations to mean that the presently *static* Mars polar ice caps (Figure 3) underwent change in the recent geological past due to increased obliquity, producing a Mars *ice age* (Head *et al*., 2003), during which portions of the water ice in the polar caps underwent sublimation and transport to lower latitudes where it was deposited as a meters-thick, dust-rich layer. This scenario has been supported by the Gamma Ray/Neutron Spectrometer experiment on board the Mars Odyssey Spacecraft (Feldman *et al*., 2002), which discovered evidence for near subsurface water ice at non-polar high latitudes that is consistent with the proposed ice ages. A major scientific question is then "What is the nature of the layers in the upper part of the North polar cap, what is the distribution of ice in the cold-traps in the circumpolar area, and how does this information bear on the age and mode of emplacement of the cap?" Using our CAVE IVR environment and the ADVISER PSE, we first investigated the distribution of unusual domical ice deposits within circum-polar impact craters to constrain the presence and post-emplacement behavior and stability of this ice (Russell *et al*, 2004; Russell and Head, 2005). The terrain visualization capability enabled us to visit, explore, and compare these deposits in rapid succession. At each candidate cold-trap, we were able to analyze in real-time the interior geometry of the deposits, their relationship to internal structure of the crater, their relationship to crater rim-crest topographic irregularities and resulting variations in solar illumination, their asymmetry and its correlation with solar illumination geometry, and the relationships of deposit geometry to local temperature-pressure conditions and regional wind directions. These data permitted us to test the long-term stability of these features and the role of insolation geometry on their shape by detailed modeling (Russell *et al*, 2004; Russell and Head, 2005).

The second part of this analysis focused on the origin of layers in the North polar layered terrain. Key questions in this regard are: (a) the nature of layers exposed in the polar cap troughs (Figure 3a through c), (b) the correlation of these layers from place to place, (c) the orientation of these layers throughout the polar cap, and (d) the relationship of the layer geometry to troughs and the structure of the cap as a whole. The CAVE was an ideal environment in which to address these questions, and the ADVISER PSE permitted us to derive quantitative data to resolve many of these questions. For example, we superposed Viking and related image data on MOLA topography to assess the broad relationship of topography, trough geometry, and layer orientation (Figure 2a and b), superposed very high resolution MOC image data (Figure 2c) to examine individual layers, their nature and sequence, and their correlation within and between troughs, and compared the orientation of individual layers in the high resolution data to topographic contours (Figure 2b) to derive layer orientations (strike and dip). These data and the related analyses permitted us (Milkovich and Head, 2005a) to: (a) recognize four vertical stratigraphic zones in the North polar layered terrain, (b) detect a fundamental approximately 30 meter climate signal in the vertical stratigraphic sequence of the upper zone of the layered terrain, (c) correlate this signal to events associated with the "recent ice age" (Head *et al*., 2003), and (d) estimate the ages of various parts of the polar cap. These data and further assessment in the CAVE and related environments then served as a basis for the analysis of the orientation of layers and the internal structure of the polar cap (Milkovich and Head, 2005b, 2005c).

Tropical Mountain Glaciers

Where does polar ice go during periods of very high obliquity? We have recently described evidence for deposits interpreted to represent the former presence of giant glaciers on the flanks of the major shield volcanoes that straddle the Mars equator (Head and Marchant, 2003). Key to the understanding of these features is the question of the former environmental conditions under which ice would accumulate in tropical areas in sufficient quantities to build these extensive glaciers (Shean *et al*., 2004). Important to success in this modeling is the visualization of the general circulation of the atmosphere of Mars under different conditions of orbital obliquity (Haberle *et al*., 2003, 2004). We are currently integrating these data to assess the general wind directions and how they might influence accumulation and ablation of the deposit interpreted to be a tropical mountain glacier. Researchers at NASA Ames Research Center are collaborating to provide the appropriate GCM parameters utilized in this research.

Planning for Exploration

On the basis of our results in the investigation of the north polar cap layer formation and evolution described above, we have used these results and outstanding questions in polar studies to formulate an exploration plan for automated and human investigations of this region. Specifically, we have undertaken in cooperation with the NASA Jet Propulsion Laboratory an analysis (the Palmer Quest design study) of the utility of nuclear power for the exploration of the polar regions of Mars. The study objectives included: (a) resolving issues of site selection and access, (b) coordinating the science objectives for a drilling station designed to penetrate the cap and a rover capability designed to traverse the cap (see Figure 3d), (c) determining the types of scientific measurements to make with both the drill and rover platforms, and (d) developing mission architecture and operational scenarios. We utilized ADVISER to: (a) convert the results of the science studies described above into specific science objectives that could be met by these platforms, (b) explore in real time for optimum landing sites from an operational and illumination geometry point of view, (c) develop traverses and tested them in terms of surface slopes and other aspects of trafficability (Figure 3e), and (d) correlate the surface exposure of layers with their predicted geometry at depth within the cap to optimize operational scenarios for co-planning drilling and rover operations and measurements.

The capability of ADVISER to put the users "on the surface" also makes it ideal for planning and training for future human exploration of Mars. We are working with Astronaut Candidates at the Johnson Space Center in Houston to develop scenarios for such exploration missions.

Ongoing and Future Work

To date, ADVISER has reached the form of a useful prototype that demonstrates the potential for planetary geoscientists to operate and analyze data in a virtual reality problem solving environment as if they were on or near the surface of a planet. We have established interdisciplinary cooperation between faculty, students and staff of the Department of Geological Sciences, the Computer Sciences Department, and the Center for Computation and Visualization at Brown University that will both define the needs for further development of the system and lead to its increasing use in academic settings ranging from freshmen geology seminars to cutting-edge research. The major challenges for ADVISER and corresponding areas of ongoing development are as follows:

Interactive Image Rendering of Large Data Sets

Rendering the highest resolution available topographic data sets at full resolution is beyond the capability of current computer graphics systems, but the volume of data that can be handled and the frame rates achievable continue to increase. Embedding multiple high-resolution images (e.g., MOC, THEMIS and HRSC) on a terrain also presents significant computational challenges for the rendering program necessitating the use of sophisticated texture simplification and paging schemes.

Incorporating Climate Model Data

For problems such as studying the polar regions on Mars, we need to visualize the general circulation of the Martian atmosphere under different conditions and time scales (e.g., seasons, eccentricity, and orbital obliquity). The primary challenges are designing the general visual representation of a high-dimensional data set and scaling a solution to support a simulation result larger than system memory.

Modeling Solar Insolation

We are working toward a virtual environment in which the scientist has control over time (and therefore, sun position) for both small and large scales (e.g., hours, decades, or hundreds of thousands of years). The challenge is computing full global illumination at interactive rates. Many techniques exist for interactively rendering shadows on height-fields, but they are typically approximations, and we are striving to make this work interactively on this large-scale data set.

Designing for Multiple Display Environments

The challenge for the ADVISER project in making full use of multiple display types (e.g., monographic desktops, stereographic desktops, and tiled wall displays) is designing the look-and-feel for each working environment. For example, keyboard and mouse control devices for a desktop are not appropriate for use in a CAVE. Similarly, user interaction metaphors will differ between some display environments (e.g., conventional desktop and CAVE).

Improved Data Integration and Communication

We are developing a portal system to transmit "virtual field notebook" data and metadata between display platform systems (e.g., between office and CAVE environments), which, among other benefits, will facilitate remote collaborative exploration. We are also improving data management facilities to provide efficient interactive access to network data repositories.

Virtual Field Instruments

We continue to develop the "field kit" and "virtual field instruments" for measuring, probing, or performing other operations within ADVISER. Many of these instruments are inspired by tools used in fieldwork on Earth as described above. Furthermore, other instruments may be inspired by the virtual environment where virtual tools can be built that are hard to create in the real world.

We anticipate that, as it evolves, the ADVISER PSE will encourage and engage multidisciplinary users in the broader scientific community through ongoing research, presentations at professional meetings, and tele-collaboration development and export to other platforms and community members over a wide range of science disciplines.

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