Planetary and Space Science 59 (2011) 1273–1279

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Integrating advanced visualization technology into the planetary Geoscience workflow

John Huffman[a,*], Andrew Forsberg[a], Andrew Loomis[a], James Head[b], James Dickson[b], Caleb Fassett[b]

[a] Center for Computation and Visualization, Brown University, 115 Waterman St., Box 1824, Providence, RI 02912, USA
[b] Department of Geological Sciences, Brown University, Providence, RI 02912, USA

ARTICLE INFO

Article history:
Received 15 April 2010
Received in revised form
4 July 2010
Accepted 5 July 2010
Available online 16 July 2010

Keywords:
Mars stereo visualization workflow analysis

ABSTRACT

Recent advances in computer visualization have allowed us to develop new tools for analyzing the data gathered during planetary missions, which is important, since these data sets have grown exponentially in recent years to tens of terabytes in size. As part of the Advanced Visualization in Solar System Exploration and Research (ADVISER) project, we utilize several advanced visualization techniques created specifically with planetary image data in mind. The Geoviewer application allows real-time active stereo display of images, which in aggregate have billions of pixels. The ADVISER desktop application platform allows fast three-dimensional visualization of planetary images overlain on digital terrain models. Both applications include tools for easy data ingest and real-time analysis in a programmatic manner. Incorporation of these tools into our everyday scientific workflow has proved important for scientific analysis, discussion, and publication, and enabled effective and exciting educational activities for students from high school through graduate school.

1. Introduction

The Brown University Planetary Geosciences group has been working with the Center for Computation and Visualization at Brown for a number of years to visualize planetary surfaces, in a way that allows for more direct exploration of the vast amounts of satellite imagery and associated digital terrain models (DTMs). This synergistic relationship has resulted in a number of highly successful visualization tools that can be used to explore these data in fully immersive environments, most notably the ADVISER Cave application (Head et al., 2005; Forsberg et al., 2006). ADVISER Cave has the ability to simulate a geologist's experience of a planetary surface and give them the virtual tools they need to explore the environment, record measurements, and engage with the data using practiced field techniques. While the ADVISER Cave application is successful as a tool to explore planetary data sets, our use of the application exposed several weaknesses in the overall design. One of the primary challenges is an incorporation of new data into the system. Bringing new data sets to the system usually required intervention by the technical team, which discourages day-to-day use of the system by the intended end-user. Another "problem" has been the vast amount of spacecraft data that has been obtained and released in recent years, which makes it challenging to keep the system up to date. Most of these images require preprocessing that requires significant computing time and much of the data being released now include stereo pairs. Since the ADVISER Cave application is designed to view DTMs and superposed textures, this stereo data could not be fully explored without processing the data into a terrain model, which is a time-intensive and complex task (e.g., Gwinner et al., 2009 and references therein). With the emergence of large scale stereo capable commodity displays, we saw an opportunity to utilize this stereo data without necessarily needing to build digital terrain models for using in the Cave. By integrating the software, we have developed for the immersive systems into a similar device that can be used within the same laboratory, where day-to-day work is being done; we could better incorporate the ADVISER program into the everyday scientific workflow, and make it an integral part of the data exploration process. To achieve these goals we had several objectives: first, to streamline the data acquisition and processing pipeline, and take advantage of the new computational resources on our university campus to better handle the volume of data being processed. Second, to design an application specifically designed to display and explore the stereo image pairs being released, with the same real-time exploration and visualization we had been doing in the Cave. Finally, it was important to bring the ADVISER Cave application into the Planetary Geology laboratory, and integrate it and the rest of the visualization tools into the workflow of the research teams. This required creating tools that are robust and easy to use, yet provide the advanced functionality that is not part of the existing tools already being used.

---

* Corresponding author. Tel.: +1 401 489 8236.
E-mail address: john_huffman@brown.edu (J. Huffman).

0032-0633/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2010.07.015

2. Data processing

2.1. Image processing pipeline

In recent years, planetary data sets have grown to many terabytes. The data that has been obtained from Mars provide a good example. Topography from the Mars Orbiter Laser Altimeter (MOLA) instrument (Smith et al., 1999) established an excellent geodetic framework. Image data from the surface have been obtained in a global or nearly global way by the Thermal Emission Imaging System (THEMIS) (Christense et al., 2008; 100 m/px in IR and ~18 m/px in Vis), High Resolution Stereo Camera (HRSC) (Neukum et al., 2004; ~12.5 to ~50 m/px), and Context Camera (CTX) (Malin et al., 2007; ~5 m/px). Along with these global-scale data sets, tens of thousands of Mars Orbiter Camera (MOC) (e.g., Malin et al., 2010) and High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) images exist at image resolutions of 25 cm–4.5 m/px. Integrating these data sets so that high-resolution images can be viewed in the appropriate context of larger-scale images (usually at lower resolution), as well as with topography, is a requirement for accomplishing science objectives.

To test scientific hypotheses, it is also critical that the data that exist be available for real-time analysis and display. For this reason, we utilize a pipeline approach for processing all of the above data sets after their release to the Planetary Data System (PDS), with the exception of HiRISE (for which we process all dedicated stereo pairs).

A description of our generic data processing pipeline is that we (1) obtain data in an automated manner using *wget* (2) use the United States Geological Survey (USGS) Integrated Software for Imagers and Spectrometers (ISIS) application (e.g., Anderson et al., 2004) to calibrate and map project images onto the Mars MOLA sphere, (3) use Geospatial Data Abstraction Library (GDAL) (Hare and Plesea, 2008) to convert data into a format that can be read on the desktop using the Environmental System Research Institute (ESRI) ArcMap Geographical Information System (GIS) (http://www.esri.com, June 2010) environment and the ADVISER applications (Geoviewer and ADVISER Desktop), and (4) tile the images with an application we developed called *tiletiff*. All of these steps are run in parallel on a per image basis, utilizing a scheduling system to handle job control. This allows multiple images to be processed at once.

The fourth step in this pipeline is critical, as *tiletiff* formats the data into a Tagged Image File Format (TIFF) file that is organized in a way that allows for rapid reading and visualizing using our visualization tools. As an added benefit, tiletiff can ensure that the image is properly formatted and carry out all error checking, then add a certification tag. In this way, it greatly simplifies data loading into the visualization application which can simply look for the appropriate TIFF tags during file loading. Like ISIS tools, tiletiff can be accessed either with a graphical user interface for ease of user interaction, or as a command line tool for pipeline integration.

2.2. Additional processing of stereo datasets

In addition to the pipeline approach that we use for all planetary image data of interest, we also have developed a specialized pipeline for stereo data sets, which are useful for examining 3D geological relationships. We use this pipeline to prepare stereo data for visualization and further analysis of all available stereo pairs. The main differences between the stereo processing pipeline and our typical image processing pipeline is that images are projected onto a smooth sphere with a local radius of the image center, calculated from the MOLA global data set. All deviations between the right and left images should then be due to topographic differences from this elevation, assuming that spacecraft location and pointing derived from SPICE kernels and camera models in ISIS are accurate.

Stereo data sets that we process programatically come from the HRSC camera, which takes stereo images for almost every observation, and from CTX and HiRISE, which routinely target stereo observations as part of their scientific operation (e.g., as of April 2010, more than ~3 TB of image data exist for HiRISE stereo images alone). Routine processing of stereo HiRISE and CTX images makes it possible for a student or scientist working on a problem to have access to three-dimensional geological relationships that may prove crucial to answering scientific questions. This allows more time to be allocated to analysis of geological relationships and less time to individually process relevant data by hand.

3. Technology

3.1. Rear projection stereo HDTVs

The initial ADVISER focus was based on our large scale, fully immersive displays, the Cave (Head et al., 2005; Forsberg et al., 2006) and tiled Powerwall (e.g., Prabhat et al., 2007). These technologies allow a user to explore a DTM and associated image data as if they are on the surface. This is done by surrounding the user with stereo capable projectors, integrated with head and hand tracking hardware. This allowed us to create virtual field toolkits, while exploring the virtual surface of Mars and the moon. This has been a very successful program, and we wanted to find ways to augment our existing applications. The emergence of large format stereo capable displays has allowed us to greatly increase our data exploration needs. Both Mitsubishi and Samsung have released rear projection televisions that are able to display stereoscopic images. These displays range in size from 52″ up to 74″, and have a resolution of 1920 × 1080 pixels. The combination of size, contrast-ratio, resolution, and stereo properties are ideal for creating and deploying Personal Powerwalls (Huffman et al., 2009): independent visualization systems with many of the capabilities of the fully immersive systems such as the Cave (Cruz-Neira et al., 1992), but the ability to run simple desktop applications on more traditional operating systems, such as Microsoft Windows, which can be implemented into the daily laboratory work-flow.

We are currently using a Samsung 62″ rear projection television in our planetary geology shared laboratory (Fig. 1). This system features a light-emitting diode (LED) lamp that increases overall system life, while reducing noise and heat, which is ideal for a laboratory with multiple workstations. The display is being driven by a high end Intel based workstation incorporating an nVidia graphics card. Due to the way the Samsung displays stereo images, a high end graphics card is not needed and almost any commodity graphics card can be used. This greatly decreases costs and complexity of the base computer system, while maintaining high end performance with greater flexibility. One of the added benefits of using a Windows based system is the ability to easily integrate various input devices into the applications. An ongoing part of the software development is designing good interaction and navigation techniques (Forsberg et al., 2009) to assist geologists in data exploration. The ability to add commodity as well as more specialized input devices has greatly increased the range of methods we can use to explore these data, and will allow us to create better interaction techniques that can be applied to our full spectrum of hardware

Fig. 1. A stereo capable Samsung 61″ display as part of a Personal Powerwall being used to explore DTM data with the ADVISER Desktop application.

and software tools. We have found the 3Dconnexion SpaceNavigator (a six degree of freedom mouse, http://www.3dconnexion.com/products/spacenavigator.html, July, 2010) of particular use for smooth panning and zooming through data with six degrees of freedom. The Personal Powerwall uses inexpensive active shutter glasses for stereo and with our current setup we can have up to 10 people viewing stereo content simultaneously. The ability for a sizeable group to participate and collaborate as new images are displayed has proven important for both research and teaching. The primary limits to the number of viewers are constrained by room size and optimal viewing angle.

3.2. *Geoviewer*

The Geoviewer, one of the key applications developed for the Personal Powerwall, was derived from a large image viewer we had developed for our tiled display wall. The original application was designed to display high-resolution images in real-time, with a set of tools that allows a user to manipulate the image properties. While we found this application to be extremely useful for data exploration, especially in a group setting, the underlying architecture of the tiled display wall made it difficult to use, and incorporating new data was non-trivial. With the increase of stereo pairs available from HiRISE, CTX, and other data streams, it became necessary to create tools to explore these data sets that were more tightly integrated into the planetary geologists daily workflow. Our solution was to create several tools that leveraged the more common commodity based displays, while drawing from our existing immersive applications. For looking at stereo pairs, specifically, we had several challenges. The first challenge is to correctly align and scale the images as a pair, and the second challenge is to create a viewer that would interactively display very high-resolution images and provide tools to better explore the data.

The Geoviewer is designed as a cross platform stereo image viewer, specifically designed for satellite image data. One of the major design goals was to ensure real-time interactivity with the data, regardless of the amount of data being viewed. The data pipeline described above results in TIFF formatted images that can easily be read into the Geoviewer, while maintaining compatibility with other applications. This allows even very high-resolution TIFF images (typically 30 × 120 k px) to be read in almost instantly. Because the image is pre-processed into individual tiles, only the data being viewed on the screen is read from disk, and adjacent data is pre-cached in preparation of the user panning or zooming, and data that is significantly off screen is flushed from memory. As a result, interactive frame rates are achievable even on low-end hardware, with fairly low memory usage.

When an image is read in, it is given a *left*, *right* or *both* designation for stereo viewing based upon spacecraft ephemeris data at the time of image acquisition (for a CTX or HiRISE stereo pair, for example, the image with the westernmost sub-spacecraft longitude is assigned to the left channel). To create a stereo pair, the left and right images are loaded in, and then assigned to the correct eye for viewing. The embedded geospatial referencing of the image ensures that the images are aligned correctly on screen, while small adjustments can be made to move the images up down left and right to ensure correct alignment. Once this is done, the stereo pair can be saved in a project file that can be loaded at a later time with all adjustments and data files preset. While the Geoviewer is designed specifically around the interlace stereo method the 3D Digital Light Processing (DLP) uses, it also supports quad buffer stereo and red–green stereo, allowing a broader scope of displays to be used to view stereo. Once an image is loaded, a user can then dynamically adjust the high and low stretch values of the image, as well as the alpha and gamma values. This allows the user to stretch the image to “pull out” the features that are most interesting, and better explore images that may otherwise be too dark or light. This adjustment is done in real-time regardless of image size using the graphics card’s hardware pixel shading. Dynamic stretching can be performed on the stereo pair as a whole or on individual left/right images, which helps in matching stereo pairs that may otherwise have color variations that may greatly reduce the stereo effect. One important part of the ADVISER program is the concept of data fusion. This refers to an integration of multiple types of data sets, with various attributes to be displayed together in an integrated visual. This is also true with the Geoviewer. Multiple images of any size and resolution can be read in and displayed simultaneously. Again using the integrated geospatial header with the TIFF image, the data is correctly aligned even at different resolutions (see Fig. 2B). For example, Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Murchie et al., 2007) spectrometry data can be overlaid with a high alpha value, giving a seamless overview of an entire area in stereo. This color blending works best when the source of the color was taken at the same viewing geometry as one of the stereo images (e.g., HiRISE color on HiRISE stereo images), or when it is possible to reasonably rectify lower-resolution color data to both of the stereo images (e.g., CRISM mineral maps on CTX or HiRISE stereo images). Once these data are combined this way, the project can be saved, ensuring that the session can be reloaded, without modifying any of the original data sources. Other features include the ability to add a Point of Interest (POI) with annotation, which can be useful for cataloging particular features within an image. The shapelib (http://shapelib.maptools.org, April, 2009) library has also been integrated into the program to allow geo-referenced ESRI Shape files to be loaded into the Geoviewer to supplement an image data. While the Geoviewer is an excellent tool for viewing satellite stereo pairs, it is not designed to replace existing tools that are already available. To supplement daily workflow, the Geoviewer is integrated directly into the ArcGIS application, as an external application. A shapefile showing the location of each stereo pair available (Fig. 2A) is used to index the data, and clicking on the location of a particular stereo pair will automatically launch the Geoviewer with that pair loaded. This increases the usability of the Geoviewer, and allows any user to quickly locate and visualize relevant stereo images, while working within their normal ArcGIS environment.

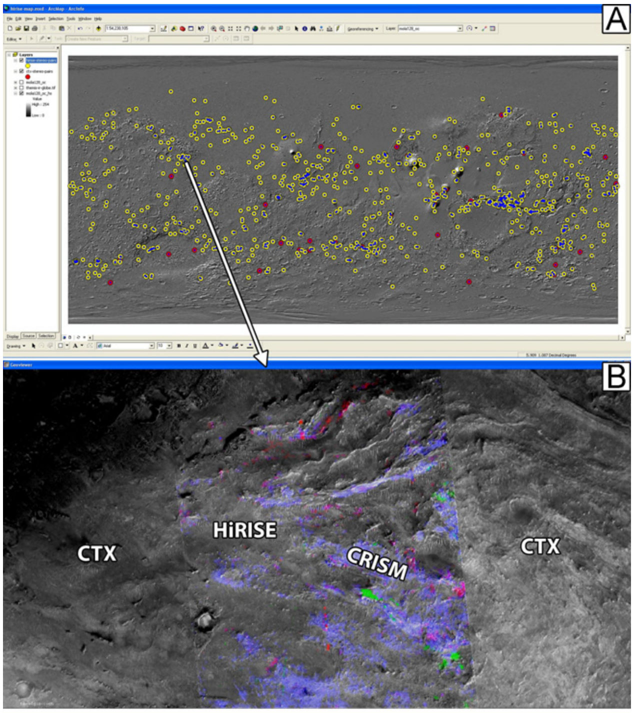

Fig. 2. (A) A global shaded relief map of Mars with a shapefiles showing the locations of HiRISE (yellow/blue) and CTX (red/blue) stereo pairs. When the individual stereo pair is clicked, Geoviewer is launched with that pair automatically loaded, as in (B). (B) Data viewed in the Geoviewer application (reproduced monoscopically here, but experienced by the user within the application stereoscopically). In this example, CRISM parameters in false color are draped over a HiRISE stereo pair, which is nested within a CTX stereo pair. CRISM orbit FRT0000B2F8 provides mineralogical mapping of ancient rocks in the Nili Fossae region of Mars (Red: Olivine; Green: Low-calcium Pyroxene; Blue: Clay minerals). HiRISE stereo (orbits PSP_006633_2010 and PSP_007556_2010) provides meter-scale topography while the CTX stereo (orbits P14_006633_2018 and P17_007556_2012) provides valuable context and topography at tens-of-meters resolution. HiRISE and CTX data were acquired in the same orbits, such that lighting illumination is consistent throughout the entire frame. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. ADVISER desktop

The ADVISER Desktop application takes the high end terrain visualization techniques from our previously developed Cave software and integrates it into a portable package, which can run on a single workstation using commodity hardware. We have focused on creating a system which not only allows us to interactively navigate, measure, and analyze DTMs from the laboratory, but also one that – much like the Geoviewer – is closely integrated into our daily workflow. The ADVISER Desktop can display both terrain models and accompanying orthoimage overlays. These data can be obtained from a number of sources, but in particular we have focused on the use of the Ames Stereo Pipeline (Broxton and Edwards, 2008; Moratto et al., 2010) to produce DTMs from existing stereo image pairs. The final inputs of this program come directly from our tiletiff application. Both the Stereo Pipeline and tiletiff are previously described in more detail in Section 2, Data Processing.

The underlying software of the ADVISER Desktop application uses a modified version of the ROAM algorithm to efficiently display large terrain models (Duchaineau et al., 1997). The algorithm works in conjunction with the tiled data sets to allow for an efficient paging of data so that only the most essential portions of the terrain are loaded into memory at a given time. As one moves through the space, the closest regions to the user are updated with higher resolution data, while the farther regions are updated with lower-resolution data. This provides a seamless interactive experience for data sets of arbitrary size. Once the images have been tiled and loaded into the application, there are many tools we can use to enhance how we view the data. These include options that allow for the adjustment of the vertical exaggeration and lighting of the terrain as well as the contrast of the image overlays. There are several options when it comes to navigation, including the mouse, keyboard, and SpaceNavigator. In addition to visualization and navigation, our application also includes a number of tools for analyzing DTMs. Using the mouse, one can quickly make measurements and place markers at points of interest. With a simple click and drag you can slice away portions of the terrain giving a profile along the line that was made (see Fig. 3). We can then export this information as either tabular data or as a raster graph for use in other applications. Additional tools such as those that allow for one to make strike and dip measurements are under development as we seek to provide a simple robust way to interactively visualize and analyze DTMs on the desktop. A crucial feature of this application is its ability to integrate with our current Cave software. While the ADVISER Desktop does run in stereo using one of the aforementioned Samsung or Mitsubishi displays, it is not nearly as immersize as our Cave environment. With that in mind our software gives users the ability to save the exact state of the application on the desktop, and then open it back up in the Cave right where they left off. It is this sort of functionality that helps us in making our software an integral part of a planetary geologists tool set.

4. Results/discussion

We have found that the Geoviewer and ADVISER Desktop platforms are most beneficial when they are used with extremely high-resolution/high-volume data sets. To help illustrate this, we now outline one example of a HiRISE stereo pair that went through the stereo processing pipeline described above and was output to the Geoviewer on the Personal Powerwall.

Fig. 4A shows a subframe of a HiRISE image of what was interpreted with lower-resolution CTX data as a late-Amazonian debris-covered glacier (Dickson et al., 2008). While surface features indicative of glacial flow are resolved in 2D imagery (downslope lineations, terminal moraine, etc.), details of the three-dimensional structure of the lobe remain unresolved. Since the density of Mars Orbiter Laser Altimeter (MOLA) tracks are insufficient to resolve this feature (300 m shot spacing), a HiRISE stereo pair at a resolution of ∼50 cm/px was acquired to determine: (1) the current topographic cross-section of the lobe to assess potential for extant ice and (2) whether the lobe consists of one major lobe or multiple smaller lobes from independent sources.

The dimensions of each acquired image (PSP_008809_2215: 54 × 18 k px and PSP_009455_2215: 55 × 20 k px) make real-time rendering and navigation in stereo challenging even for high-end desktop workstations. The tiling algorithm described above and used in the ADVISER stereo pipeline (tiletiff) alleviates these issues and allows for seamless and fluid rendering of both images in an active stereo with instantaneous response to user inputs. Once these images are tiled, they are displayed on the Personal Powerwall in Geoviewer at a resolution of 1920 × 1080. While the resolution is comparable to desktop monitors, the physical dimension of the display (61″ diagonal) facilitates group discussions of up to 10 participants, something not possible on a desktop workstation. This physical size can be achieved via digital

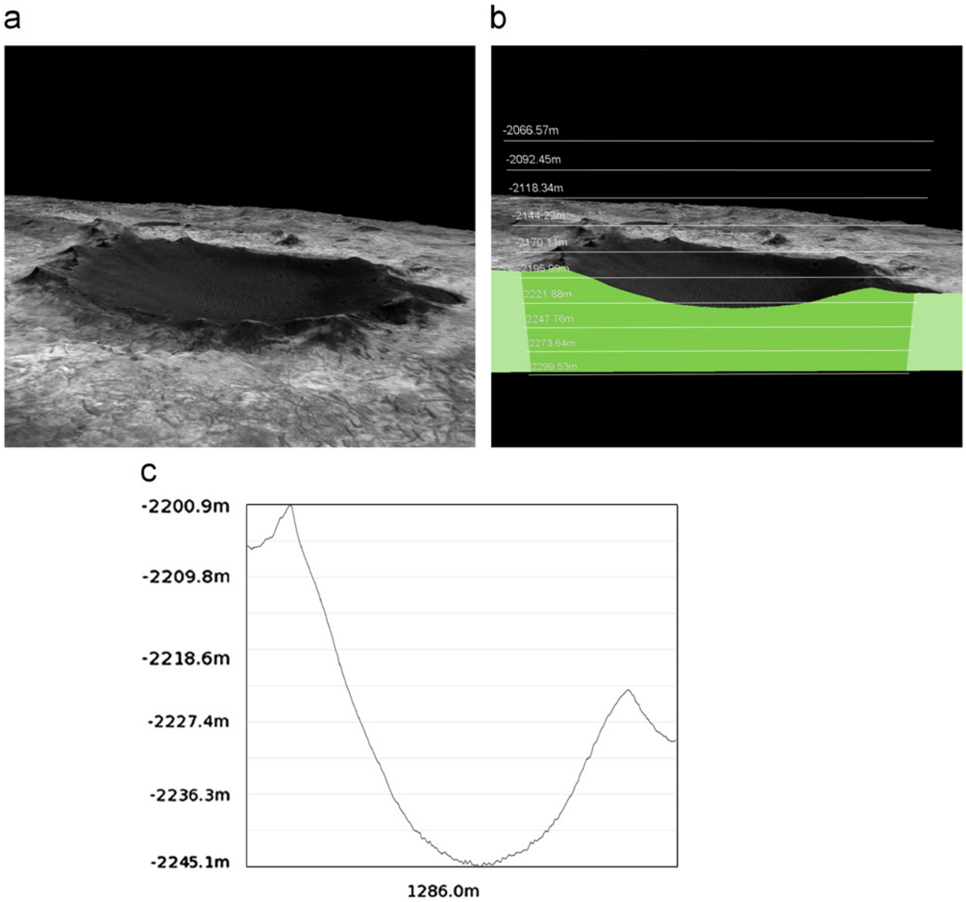

Fig. 3. (a) View of a crater in the Mawrth Vallis region seen in the ADVISER Desktop application. The terrain and image data are obtained from HiRISE (orbits PSP_010816_2040 and PSP_010882_2040). (b) A slice plane and profile through the terrain created by dragging the mouse across the surface. (c) Graph created from the same profile.

projectors, but at the expense of resolution, contrast-ratio, or both. This allows for several experts from various sub-disciplines to contribute and add perspective to complicated geological problems.

In the aforementioned example, the processed anaglyph (Fig. 4B and C) reveals neighboring convex-up lobes trending downslope within the broader lobe, suggesting that there may be multiple smaller lobes of ice still present beneath a debris cover. While these topographic relationships can be seen in traditional red/blue anaglyphs, tracing these lobes upslope to their respective source regions requires displaying the data at resolutions and physical dimensions that are inconvenient with printed anaglyphs or standard desktop monitors. When the details of these nested lobes are viewed in context, the eastern lobe appears to be sourced at the headwall of the tributary, while the western lobe is sourced along the western sidewall escarpment. These detailed relationships aid geologists who attempt to assess the most-likely accumulation zones for ice in the late-Amazonian period of martian history.

The transition from traditional red/blue anaglyphs to active stereo on the Personal Powerwall allows for the integration of color and hyper-spectral data within stereo data sets. For instance, we have produced automated code that is able to process HiRISE color data for the center 20% of all HiRISE stereo pairs. This color information is lost in traditional red/blue anaglyph renderings, but is revealed on the Personal Powerwall. In certain instances, CRISM parameter maps have been registered with the stereo HiRISE images to allow mineralogical analysis of exposed surface units in the stereo environment (Fig. 2B). This has proven particularly valuable for discussions of potential landing sites, where distinct mineralogical units can be viewed within their topographic and stratigraphic context and assessed for viability with the Mars Science Laboratory (MSL). With the recent acquisition of high-resolution hyperspectral data from the moon from the Moon Mineralogy Mapper (M^3) (e.g. Pieters et al., 2009) and stereo imagery from the Lunar Reconnaissance Orbiter Camera (LROC) (Robinson et al., 2010; Beyer et al., 2010), we plan on performing similar analyses of compelling geologic terrains on the Moon. All platforms that have been developed through the ADVISER program are designed to be versatile enough to incorporate data from all planetary surfaces.

5. Future work

With the recent release of the Ames Stereo Pipeline, it will now be possible to create DTMs from any of the stereo pairs that we already have, as well as future releases. Moreover other processing pipelines for planetary stereo images exist that have been proven to produce high quality DTMs, many of which are now being publically released (e.g., Kirk et al., 2008; Gwinner et al., 2009).We are currently integrating this Ames Stereo Pipeline, as well as fully processed, publically released DTMs, into datasets for scientific exploration using our software. As these datasets continue to grow, and new data sets from M^3 and LROC cover an ever expanding area of the Moon, we are working on ways to visualize entire planetary surfaces both on the desktop and in the Cave immersive environment as a whole. This presents challenges

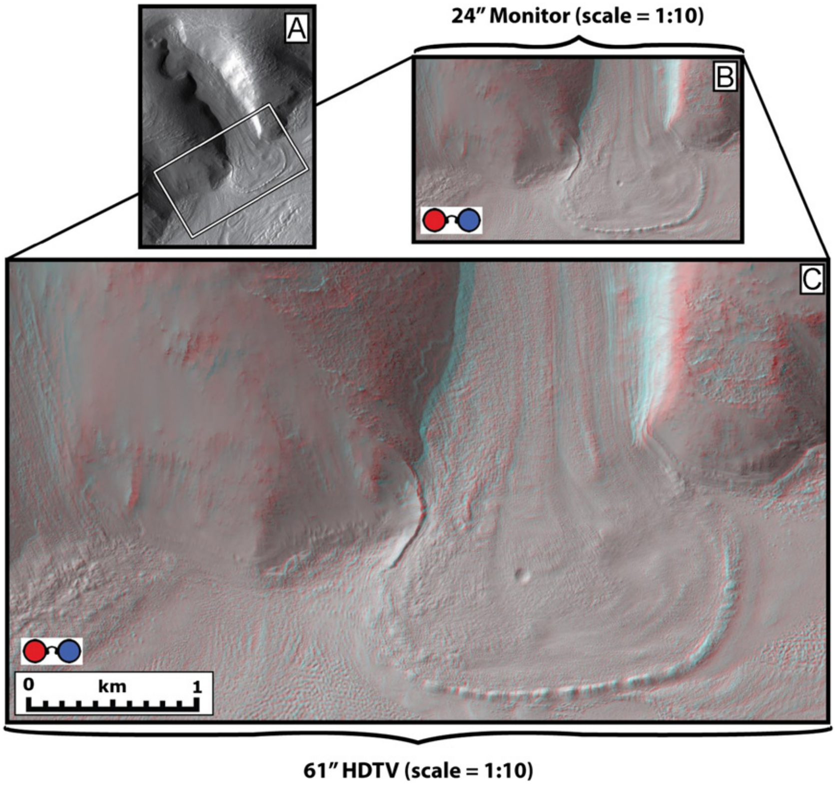

Fig. 4. (A) Subframe of HiRISE orbit PSP_008809_2215 showing a late-Amazonian debris-covered glacier in a tributary valley in the Protonilus Mensae region of Mars (Dickson et al., 2008). (B) Red/blue anaglyph of the distal lobe of the glacier (HiRISE orbits PSP_008809_2215 and PSP_009455_2215). The anaglyph has been scaled to 1:10 the size of a 24″ desktop monitor. (C) The same anaglyph but scaled to be 1:10 the size of the 61″ Personal Powerwall to show the relative increase in display size. The large physical dimension of the Personal Powerwall and high-resolution of the display allow for detailed observations within the broader context of features of this scale. In this instance, individual lobes of possible buried ice within the broader lobe can be traced upslope to the headwall of the valley and the western sidewall escarpment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in data management, image projection, and scalable visualization techniques. We are also in the process of developing the next generation of Cave technology that promises to be much brighter, larger, and with two orders of magnitude more resolution than our current Cave technology. This will pair nicely with the increase in resolution and data imagery available, and we are continuing to incorporate changes into the ADVISER Cave application that will take advantage of this new display technology. Overall, we have found that these displays and tools integrate nicely into the way we look at and explore planetary imagery and DTM data. The data processing pipeline greatly simplifies how we ingest new data into our laboratory, which allows us to begin our analysis much sooner and with little overhead. Preprocessing also allows us to seamlessly integrate these data sets into the visualization applications we have developed, greatly contributing to our existing tool set and filling a gap presented with the new stereo image sets. These tools have enhanced our ability to analyze and understand complex data, and have become an integral part of how we do research at Brown.

Acknowledgements

We would like to thank NASA's Applied Information Systems Research Program (Grants no. NNG05GA61G and NNX08AC63G) for supporting this work. CRISM data and helpful discussions were provided by Jack Mustard. We thank Alfred McEwen and the HiRISE team for specially targeting in stereo the feature observed in Fig. 4 and for producing and releasing the DTM shown in Fig. 3. We would also like to thank Mr. Prabhat and Mark A. Duchaineau for work that greatly contributed to the success of this program.

References

Anderson, J.A., Sides, S.C., Soltesz, D.L., Sucharski, T.L, Becker, K.J., 2004. Modernization of the integrated software for imagers and spectrometers. Lunar and Planetary Science Conference XXXV, abs. no. 2039.

Beyer, R.A., 15 co-authors, 2010. LROC stereo data—results and initial analysis. Lunar and Planetary Science XLI, 2678.

Broxton, M.J., Edwards, L.J., 2008. The ames stereo pipeline: automated 3D surface reconstruction for orbital imagery. Lunar and Planetary Science Conference XXXIX, abs no. 2419.

Christensen, P.R, 10 co-authors, 2004. The thermal emission imaging system (THEMIS) for the Mars 2001 odyssey mission. Space Science Reviews 110, 85–130.

Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., Kenyon, R.V., Hart, J.C., 1992. The CAVE: audio visual experience automatic virtual environment. Communications of the ACM 35 (6), 64–72.

Dickson, J.L., Head, J.W., Marchant, D.R., 2008. Late Amazonian glaciation at the dichotomy boundary on Mars: evidence for glacial thickness maxima and multiple glacial phases. Geology 36, 411–414.

Duchaineau, M., Wolinsky, M., Sigeti, D.E., Miller, M.C., Aldrich, C., Mineev-Weinstein, M.B., 1997. ROAMing terrain: real-time optimally adapting meshes. In: Proceedings of the 8th Conference on Visualization '97, IEEE Visualization, pp. 81-88.

Forsberg, A., Prabhat, G., Haley, A., Bragdon, J., Levy, C.I., Fassett, D.E., Shean, J.W., Head, S.M., Milkovich, Duchaineau, M.A., 2006. Adviser: immersive field work for planetary geoscientists. IEEE Computer Graphics and Applications 26, 46–54. doi:10.1109/MCG.2006.73.

Forsberg, A., Huffman J., LaViola J., Dickson J., Fassett C., Zeleznik R., Chen J. and Head J., 2009, A head-to-head comparison of navigation techniques for exploring 3D geoscience data sets, Poster/Demo, ACM Siggraph Symposium on Interactive 3D Graphics and Games.

Gwinner, K., Scholten, F., Spiegel, M., Schmidt, R., Giese, B., Oberst, J., Heipke, C., Jaumann, R., Neukum, G., 2009. Derivation and validation of high-resolution digital terrain models from Mars express HRSC data. Photogrametric Engineering and Remote Sensing 75 (9), 1127–1142.

Hare, T.M., Plesea, L., 2008. Planetary GIS updates for 2007. Lunar and Planetary Science Conference XXXIX, abs no. 2536.

Head, J.W., van Dam, A., Fulcomer, S., Forsberg, A., Prabhat, Rosser, G., Milkovich, S.M., 2005. ADVISER: immersive scientific visualization applied to Mars research and exploration. Photogrametric Engineering and Remote Sensing 71, 1219–1225.

Huffman, J.N., Forsberg, A.S., Head, J.W., Dickson, J.L., Fassett, C.I., 2009. Testing geoscience data visualization systems for geological mapping and training. Lunar and Planetary Science Conference XXXX, abs no. 2086.

Kirk, R.L., 18 co-authors, 2008. Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: meter-scale slopes of candidate phoenix landing sites. Journal of Geophysical Research 113, E00A24. doi:10.1029/2007JE003000.

Malin, M.C., 18 co-authors, 2007. Context camera investigation on board the Mars reconnaissance orbiter. Journal of Geophysical Research, 112. doi:10.1029/2006JE002808.

Malin, M.C., Edgett, K.S., Cantor, B.A., Caplinger, M.A., Danielson, G.E., Jensen, E.H., Ravine, M.A., Sandoval, J.L., Supulver, K.D., 2010. An overview of the 1985–2006 Mars orbiter camera science investigation. Mars 5, 1–60.

McEwen, A.S., 14 co-authors, 2007. Mars reconnaissance orbiter's high resolution imaging science experiment (HiRISE). Journal of Geophysical Research, 112. doi:10.1029/2005JE002605.

Moratto, Z. M., Broxton, M. J., Beyer, R. A., Lundy, M., Husmann, K., 2010, Ames Stereo Pipeline, NASA's Open Source Automated Stereogrammetry Software, In: Proceedings of the 41st Lunar and Planetary Science Conference, abs. no. 2364.

Murchie, S., 49 co-authors, 2007. Compact reconnaissance imaging spectrometer for Mars (CRISM) on mars reconnaissance orbiter (MRO). Journal of Geophysical Research 112, E05S03. doi:10.1029/2006JE002682.

Neukum, G., Jaumann, R., the HRSC Co-Investigator Team, 2004. HRSC: the High Resolution Stereo Camera of Mars Express. Mars Express: the Scientific Payload. European Space Agency Special Publication ESA-SP1240, 17-36.

Pieters, C.M., 28 co-authors, 2009. Character and spatial distribution of OH/H_2O on the surface of the Moon Seen by M^3 on Chandrayaan-1. Science 326, 568–572.

Prabhat, Forsberg, A., Head, J. W., 2007, Seventh International Conference on Mars, abs. no. 3326.

Robinson, M.S., 22 co-authors, 2010. Lunar reconnaissance orbiter camera (LROC) instrument overview. Space Science Reveiws 150, 81–124.

Smith, D.E., 18 co-authors, 1999. The global topography of Mars and implications for surface evolution. Science 284, 1495–1503, doi:10.1126/science.284.5419.1495.