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Geologic Mapping in Mars Rover Operations

Mark W. Powell, Thomas M. Crockett, Jeffrey S. Norris and Khawaja S. Shams
Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA 91109

Geologic mapping of the Martian surface has been a goal for every mission to Mars in history. Surface rover missions bring with them unique capabilities and intrinsic challenges for the task of mapping. The diversity of the terrain that is encountered as a rover traverses is a challenge that is being addressed by two major mapping strategies: on-board autonomy and ground operations software. Here we present our latest work in the use of ground operations software that extends and enhances the work done in autonomy to provide accurate localization and mapping capabilities for rover missions. These results demonstrate how our ground tools have had the most impact to date of any similar work in this field—both in rover mission science operations and in the global Mars science community.

I. Introduction

THERE are few things that have had as significant an impact on Mars surface operations in the last several years as the availability of high resolution orbital images for mapping. In particular, the High-Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter (MRO) has provided many invaluable and indeed unforgettable images to aid these missions. Its imaging captured the Phoenix Mars Lander spacecraft during its entry, descent and landing on the surface in May 2008[1]. Its campaigns of image collection over all of the proposed landing sites for the Mars Science Laboratory (MSL) mission are enabling to the teams who are assessing the accessibility of these sites. For the Mars Exploration Rovers (MER) Spirit and Opportunity, HiRISE images of their regions of exploration are an integral part of daily science operations planning.

HiRISE images of the surface are currently the highest resolution orbital images of Mars available. The highest resolution images from HiRISE capture the terrain at a spatial coverage of 0.25 meters per pixel. At this resolution, many details of the surface are visible at relatively small scales, such as large rocks that could be obstacles at a rover landing site, or a rover itself (albeit in only handful of pixels) along with the tracks it has recently made. For geologic mapping, where all of the various *units* (regions of common attributes at a given scale) and their *contacts* (borders that lay between adjacent units), this additional resolution expands the science community's ability to map units at scales higher than ever before. Registration of HiRISE imagery with datasets from other orbiting instruments adds additional context to these observations and gives added support (or prompts revision of) hypotheses about the history of Mars. Stereoscopic algorithms that use pairs of HiRISE images of the same surface area from different points of view can produce digitial elevation maps (DEMs) that are useful to analyze the topography of the terrain.

Mars surface landers and rovers since Sojourner in 1997 have also been equipped with stereo imaging capabilities. For example, the MER navigation cameras (Navcams) capture 1 megapixel stereo images of the surface from a height of about 1.5 meters above the surface from a mast that can turn to point the cameras any area on the surface. The Navcams are a stereo pair of cameras with a 20 cm baseline that can range terrain point up to a distance at up to 20 meters and can be used to produce a dense terrain mesh up to about 10 meters from the rover. For every stereo image pair that is downlinked, the mission ground data system creates a point cloud (XYZ map) product for that pair. For geologic mapping, it is desirable to repackage the point cloud data into an elevation map that illustrates the topography of the terrain when viewed from above. The Navcam elevation map is also straightforward to integrate with a DEM produced from HiRISE images by overlaying the two.

Prior to the Mars Exploration Rover mission (MER), it was unclear whether geologic units and their contacts would be present, preserved, or even detectable from observations at the surface with a remotely operated rover. It is now clear that geologic mapping on Mars need not differ from that on Earth. The previous state of practice of remote field geology on Mars was somewhat haphazard due to the limitations of remote robotic vehicles and unknowns in the environment. Geologic mapping of field observations into a single, registered regional map is straightforward on the Earth by using standard surveying techniques (i.e. Total Station, Global Positioning System

(GPS) referencing, etc.) for triangulation and measurement of position and distance. With a rover on Mars, however, only relative position estimation is possible as there is no convenient infrastructure for world-referenced position estimation like GPS to support planetary exploration. During a traverse, each drive step makes new position estimates relative to the last estimated position, leading to an accumulation of error with each additional step. The error in position estimation can be very significant. For example, the MER rovers can estimate their position and attitude with a nominal error margin of 10% by a combination of wheel odometry, sun finding, and IMU (inertial measurement) data[2.] In some circumstances, high wheel slippage on the terrain results in the as-telemetered estimated drive distance being significantly greater than the actual drive distance. For example, in Eagle crater at Meridiani Planum, the Opportunity Mars Exploration Rover encountered extremes of slopes and loose soils which resulted in 100% slippage (no forward motion) during many of its traverses. While other techniques may be integrated onboard a rover to reduce localization error, they are not yet inexpensive enough to be used under all circumstances. One such technique called visual odometry[3] uses image-based feature correlation to estimate changes in rover position with much greater accuracy compared to dead-reckoning and other naïve localization techniques. The process on MER, however, currently requires 2 to 3 minutes per drive step. (The length of a drive step can vary based on the terrain, but is typically 2 to 3 steps per meter traversed.) Often the science goals of the mission are too time-consuming to allow time for visual odometry to execute onboard. Science investigators frequently decide to forego onboard location refinement in favor of executing more science observations. Thus, the problem of location refinement is postponed.

It is possible to manually eliminate much of the error in position estimation by careful analysis of telemetered image data. Science investigators can analyze the imagery and identify features common to images taken from more than one rover position and use stereo triangulation to compute XYZ locations for each feature. By comparing 3 or more feature locations in images taken both before and after a drive, the rover's change in position can be estimated. This location refinement process as currently performed for MER mission operations historically required several weeks to be performed and applied retroactively to a set of geologic observations, all of which are several weeks old by the time the results are available. This delay is simply a characteristic of the previous state of practice of geologic mapping with the rover data by the collective MER science team.

It is not straightforward to apply techniques that are used onboard the rovers to correct localization after the data is transmitted to Earth. Visual odometry, for example, improved localization by tracking features in images taken at a certain distance from the rover at every drive step over an entire traverse. It will not often be the case that enough of this collection of images will have been transmitted to Earth in time to support the next tactical planning cycle (if ever); higher priority data may preclude transmitting enough of the images in the available bandwidth, or data dropout may prevent key images from arriving until the next available transmission opportunity many hours later after the tactical process is already committed to a science plan that cannot be easily changed. Instead, we put operational tools to the task of correcting localization knowledge in a timely fashion in order to make a consistent, significant impact on the way we conduct geologic mapping with the rovers.

One historical approach to geologic mapping in MER operations involves manually aligning overhead-projected image mosaics using a photo-editing tool. The analyst visually correlates two or more mosaics to create a new layer for a geologic map (see Fig. 1). Optionally, orbital images of the traversed surface are also manually overlaid with the surface image mosaics to create a more comprehensive map.

It is a straightforward extension of this mosaic alignment to produce localization correction as an output in addition to a layer for a geologic map. Ideally, a mapping tool

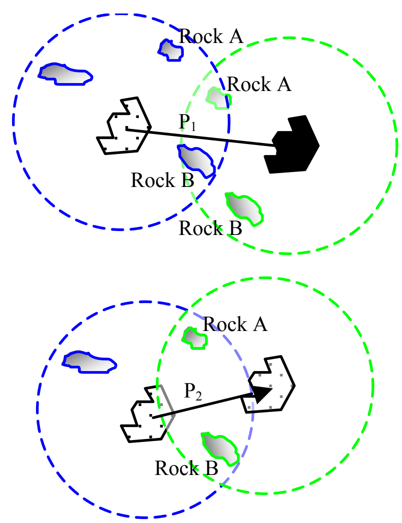

Figure 1. Alignment of two overhead mosaics of surface images taken from two different rover positions. Above: miscorrelation of surface features (Rocks A and B) from localization error. Below: improved correlation of surface features and estimated rover position after manual image alignment.

that is integrated with a targeting and planning tool would provide an effective means of manually aligning the relative locations of image mosaics while also producing a corrected estimate of vehicle position. As a result, science planning benefits from operating in the context of the maps that can be generated in the planning tool in the beginning of the tactical process. In the end the entire science team benefits from both greater knowledge of the geologic setting and from improved support for science targeting that enables accurate reuse for future targeted science observations.

The "bundle adjustment" location refinement process[2] has been successfully applied to MER location telemetry and has produced significantly improved location estimation. The bundle adjustment process considers images from both orbital cameras and rover cameras and establishes a network of common feature points called control points that appear in the images. Control network image registration is a technique dating back decades that is used to coregister collections of science observations from different instruments on planetary and lunar orbiters. The bundle adjustment process continuously adds new sets of surface images and orbital images as they become available. The technique has been shown to reduce estimated location error to less than one percent. However, the process is computationally intensive and requires several days (3 or more) to produce results.

Bundle adjustment and location refinement by science investigators used together may be a mutually beneficial pairing. If an initial refinement is performed by an investigator relatively quickly (in an hour or less) to provide significantly better location estimation for targeting during the tactical process, that information may also be useful as an superior input to bundle adjustment as a better initial seed, or estimate. The eventual update of the control may result in location estimation of greater accuracy and would likely require less compute time than would have otherwise been required, owing to the improvement to the initial estimate.

Although it is useful to have this improved geometric information to inform the long-term science planning decision process—albeit weeks after the observations in question are returned—it would be far more valuable to have this information on a daily basis to inform the tactical science process. To achieve this, we focused on techniques and algorithms that can produce significantly better location results but may be executed in an hour or less. This time constraint is dictated by the tactical planning schedule for Mars surface operations which requires that targeted science observations be ready 1 to 2 hours after tactical downlink data analysis is complete.

II. Maestro Map View

The Maestro Map view is a map browsing user interface that encompasses the entire region of exploration for a Mars surface exploration mission. An example of the Map view is shown here in Fig. 2. The map is interactive, allowing the user to pan in any direction by clicking and dragging or to zoom in or out by scrolling the mouse or touchpad. A thumbnail viewer in the upper left of the view displays a scaled down version of the entire map with a yellow rectangle indicating the area that is being shown in the main view area. This rectangle is also interactive and allows for click-and-drag navigation over the map at a fixed zoom level. The user may also optimize the detail over any area of the map by right clicking and dragging a rectangular region of interest, causing the view to zoom to fit that area in the view window at the optimal scale. In the upper right corner the current zoom level is displayed as a numeric percentage and allows the user to click to enter a precise scale amount. A legend at the lower left provides a reference to give features on the map a sense of scale. Just above the upper right corner of the map view there is a set of tool icons. This set currently includes tools for scaling the view, a query tool for displaying detail on a selected point of interest, and a ruler tool for displaying the distance between and positions of two points of interest.

Displaying a map of the entire region of interest of a Mars surface exploration mission can get rather large. In the example shown in Fig. 2, we use a map that is 60763 by 129774 pixels (7.89 gigapixels) in size. An image of this size is too impractical to load entirely into memory for any contemporary laptop computer, which is our target platform for the Map view. Our strategy of choice to address this challenge in scale is to provide the map image as tiles delivered on demand. We begin by sectioning the full resolution map image in advance into tiles of equal size. We then scale the image down by two and repeat the tiling. We continue iterations of scaling and tiling until the reduced map image fits within a single tile. This delivery system is explained in greater detail in Ref. 4. Given this tiling of the image, the Map view can request the set of tiles that are most appropropriate for the current map viewing scale and the current region being viewed. We make the on-demand download of tiles as efficient as possible using JPEG2000 image compression to achieve an optimal quality to bandwidth ratio.

The traverse path of the Opportunity Rover as of this writing is displayed on the map as a white line. When the scale of the map increases enough (>= 5%), diamond-shaped markers appear on the path at every location where there are three or more Navcam stereo image pairs that have been downlinked from the rover. When the scale increases to 50% or more, Navcam mosaics at each of these locations are overlaid on the map. Like the map itself,

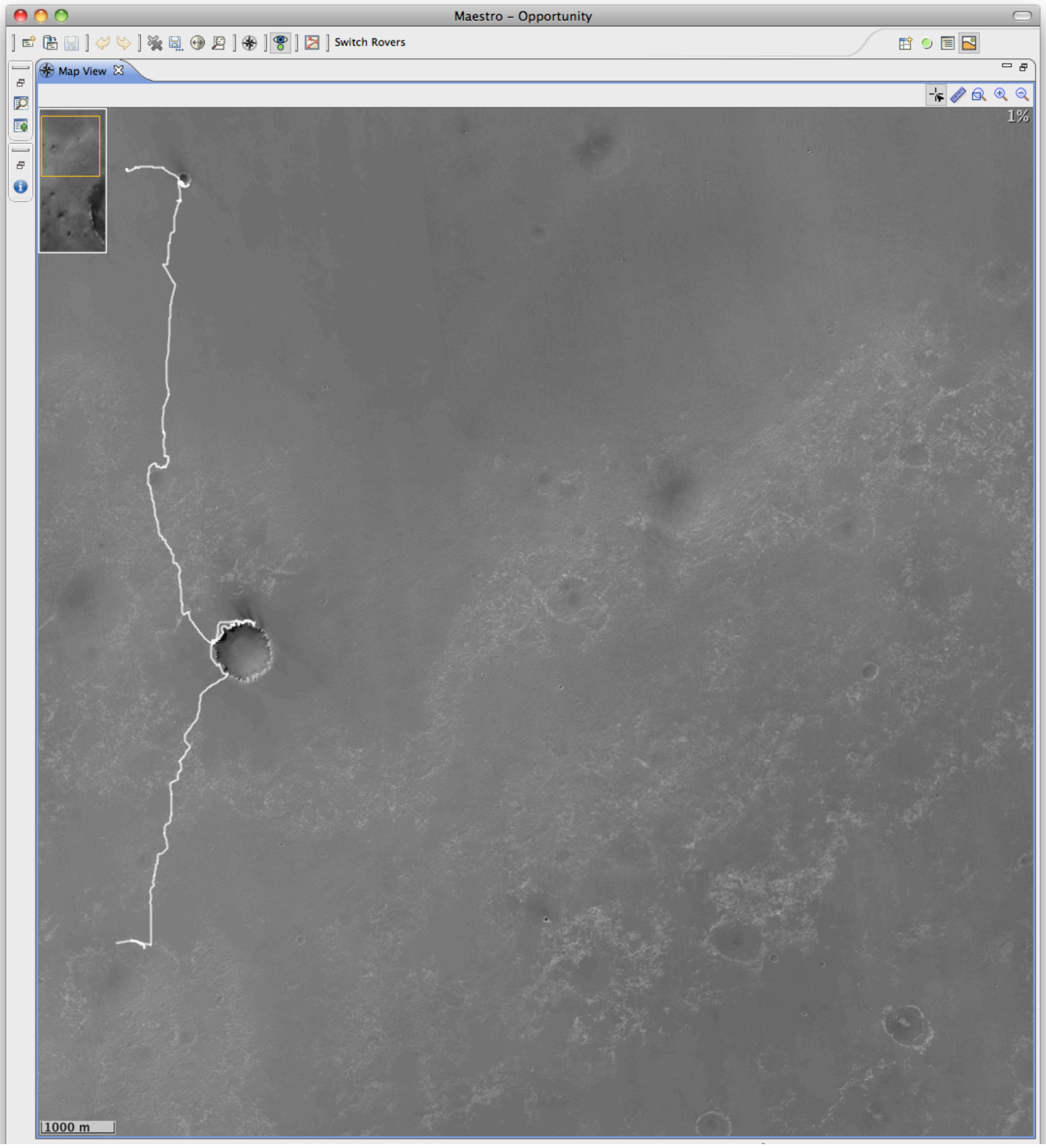

Figure 2. The Maestro Map View displaying the region in Meridiani Planum surrounding the traverse of the Opportunity Mars Exploration Rover.

the Navcam mosaics are requested in a tiled fashion so that only images with an appropriate level of detail for the scale of the map are downloaded. At the highest resolution, the Navcam mosaics show the terrain at 0.01 meter resolution. The mosaic position markers provide additional actions as well, such as to query mission data from other instruments that were acquired at that location or to view activity plans that were scripted for uplink to the rover while at that location. The map can also overlay icons with place names that correspond to science targets and other named features on the terrain for these locations.

Another advanced capability that the traverse path provides is interactive localization correction. Each traverse location that has a Navcam mosaic is selectable via clicking on its center diamond. For many locations, there is at first a noticeable difference in positions of features that are present both on the map and in the Navcam mosaic. After each traverse, there is 10% error on average in localization. For example, given the common case of a 100 meter drive at Meridiani Planum, the reported position of a mosaic on the map is typically off by 10 meters (with

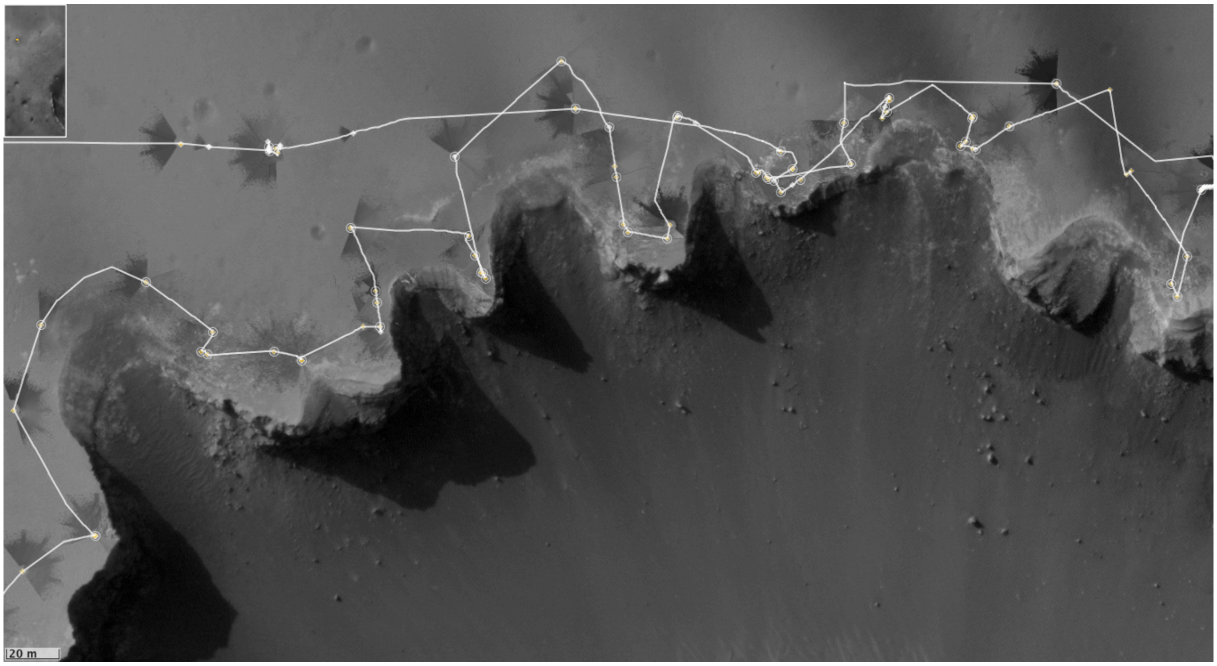

Figure 3. Map view displaying the north rim of Victoria Crater with the rover traverse path (the white line) and Navcam mosaics overlaid onto the map.

respect to the map) at the final traverse location. The diameter of each Navcam mosaic is 30 meters, so this misalignment is quite substantial. In order that the mission science analysts and tactical planners can correct for this error on the ground immediately after the data downlink, the Map view allows each position to be selected and then dragged to its correct position with respect to the map based on any criteria available to the user such as feature registration or landmark triangulation. The feature registration technique is both very reliable and efficient. In our previous work, we discussed how individual point target designations may be corrected for localization error after a traverse in the context of science planning[5]. In the Map view, localization correction by the alignment of a Navcam mosaic with map features is equivalent to redesignating thousands of individual target points simultaneously. The resolution of the Navcam allows for localization correction to be performed that reduces the error at each rover position to the nearest 0.01 meter. This improvement in error correction is orders of magnitude greater that the previous state of practice.

The Map view makes the user interaction for correcting localization intuitive and responsive. It is a straightforward action to select a Navcam mosaic for a location and move it to its correct position on the map. The Map view seamlessly makes updates to the surrounding traverse path geometry as the user moves a position. In order to align Navcam features properly to the same features in the HiRISE image, the Navcam mosaic becomes partially transparent during the drag, allowing the viewer to make minute adjustments to determine the most accurate position alignment. There is also an action for controlling Navcam mosaic visibility via a checkbox that allows the viewer to choose to "Show only this mosaic." For areas where they are many overlapping Navcam mosaics, the user can view by default all the Navcam mosaics and register each one to its neighbor, or activate "Show only this mosaic" to make only the Navcam mosaic being adjusted visible to register it to the HiRISE image without any clutter of other Navcams in the view. Both modes of interaction are useful and can be used one after another where applicable to provide additional verification of Navcam positioning.

III. Algorithms

In order to make the Map view sufficiently accurate, responsive and interactive for tactical geologic mapping and science operations planning, we created several innovative software features. In the next sections we will discuss the three most interesting innovations for interactive mapping: Navcam DEM creation, the fabric stretch algorithm and dynamic overlaying.

Figure 4. Map view displaying an Opportunity rover Navcam mosaic overlaid on the map at high resolution overlaid on a HiRISE map. The legends in the top and bottom images show scales of 1 meter and 5 meters, respectively.

A. Navcam DEM creation

To create an accurate overlay of Navcam stereo images onto a map made from one or more HiRISE images and possibly other data from orbital instruments, the Navcam stereo images must be reprojected to match the HiRISE. For our work we use HiRISE imagery that is projected into the equirectangular cylindrical map projection. In this map projection, the distance between horizontal and vertical pixels is equivalent to a fixed increment in longitude and latitude, respectively. For regions of the surface that are as limited as those that are explored by a Mars lander or rover, it is valid to assume that the distance between pixels is equivalent to a fixed increment in meters in a

Cartesian coordinate system rather than the spherical system of latitude and longitude. Using a Cartesian coordinate system is the convention for planning rover activities, so it is advantageous to work in units of meters.

The construction of a Navcam DEM begins with selecting an approrpriately sized rectangular bounding box for the horizontal and vertical elevation (height) values. We chose to create height maps having a 30 by 30 meter surface area with height values evenly spaced at every 2 cm and with the rover coordinate frame origin placed in the center. The size was chosen after studying many Navcam stereo datasets and observing that the useful data generally extends to a distance of 10 to 12 meters from the rover with occassional exceptions. A bounding square of 30 meter width provides ample surface area to capture all of the useful stereo data. The spacing between height values of 2 cm increment was also chosen based on observations of the density of height maps over a range of resolutions. The 2 cm spacing is the optimal height map pixel size yields the optimum tradeoff between terrain fidelity and an overabundance of missing height values.

Because the Navcam stereo image pairs are captured from a high incidence angle from the surface, their DEMs are quite unlike those constructed from orbital image pairs. Holes in the elevation map are generally abundant in regions that lay behind rocks or where sloping terrain creates similar obscurations. It is also impossible for any of the rover stereo cameras to see the terrain underneath the vehicle, so there is always a large area of missing height values of approximately 1 meter diameter in the center in the map with additional missing values where rover parts such as solar panels and antennae obscure the terrain.

The algorithm for constructing the DEM takes as input the stereo XYZ point cloud and produces an array of height values. To determine the height value at each X-Y pixel coordinate, we iterate over all of the XYZ points and make a list of all of them that fall within the 2 by 2 cm area for that pixel. Once we have captured all of the candidate points for that height map pixel, the highest height value is assigned as the height map pixel value. Once the entire height map has been constructed by taking the highest values that fall within each cell, there are sometimes outlier points in the XYZ cloud that appear as elevation spikes that thrust upward from the terrain. These presence of these outliers can be due to errors in the stereo data or due to artifacts in the original images themselves. In order to remove the outliers, we refine the height map by applying a 7 by 7 pixel median filter over the map. This operation computes the median height value over a 7 by 7 pixel neighborhood centered on each pixel and assigns that value to that pixel. In conventional digital images, this filter is often applied to remove "salt and pepper noise" that appears as abnormally bright or dark pixels that are outliers. This same operation applied to the height map removes the outliers while maintaining the integrity of the terrain morphology. We have applied this DEM generation technique to thousands of MER Navcam stereo image datasets and our observations show that this technique is generally effective for producing accurate DEMs without outliers that are suitable for geologic mapping.

B. Fabric Stretch correction algorithm

Performing localization corrections of each Navcam location is an enabler for tactical geologic mapping. In order to make informed decisions regarding the science opportunities in the current planning cycle, the interface must allow a user to make corrections to new post-traverse locations as soon as possible once the new Navcam data is available. The Map view interface affords this fast interactive correction capability by allowing the user to select any Navcam location on the traverse path, then click and drag it to its correct location. When this happens, the traverse path moves two clusters of traverse path points along with the selected location. The first cluster is the set of path points that occur before the selected position, going back to the most recent corrected position (or the initial position if none are yet corrected). The second cluster is the set of path points that occur after the selected position, going forward to the most recent corrected position (or the final position if none are yet corrected). The rover reports a total set of traverse points that captures many more positions than those where Navcam images are downlinked. The path correction algorithm seeks to adjust these collections of path points so that the points that lay between corrected positions remain true to their inherent relative geometric layout. For example, for the case of a straight line traverse from corrected position A to B, a correction to B that lengthens the magnitude of the vector AB propagates the increased scale to each of the intermediate path segments that connect A with B such that each the updated position of each point is adjusted in the direction of AB by a fraction of the movement of B relative to A. The fraction of movement of each intermediate point is determined by its relative position to its neighbor path points. The movement of the cluster as a unit effectively scales the polyline with endpoints AB according to the correction applied to B. The second type of correction to B is a rotation to correct the direction of the vector AB. If the rover slips in a direction orthogonal to its drive direction, or if it performs a complex arc or set of arc movements, its reported drive positions may have error requiring correction by rotation. Thus, dragging the point B to rotate it relative to A will also rotate the set of intermediate points that form the polyline with endpoints AB. We have named this algorithm of collectively correcting a set of traverse points via rotation and scale the *fabric stretch* algorithm. The transformation is effectively as if the points were laid out on a piece of fabric that is stretched in the direction of AB and rotated to align with features on the basemap.

Figure 5 shows the iterative process of correction while dragging a location. The black arcs represent the complete set of traverse positions between a corrected point A and a point B that is actively being corrected. B_{orig} is the original position of B prior to correction. The user then drags B through B_{prev} to B_{curr}, which may either be the final corrected position or may be an intermediate position on the way to the final corrected position. The red lines denote the vectors between A and each of the various B points. For each mouse drag event during a correction, the algorithm performs three steps on the set of points that define the arc AB. We will describe precisely the events that occur for the event associate with dragging from B_{prev} to B_{curr}. First, the set of points B_{prev} and all intermediate points on the arc AB_{prev} are rotated about A by the angle $-\theta_1$. Second, the set of points is scaled uniformly in the direction of AB_{orig} such that the distance AB_{prev} is equal to the distance AB_{curr}. Lastly, the set of points is rotated about A by the angle θ_2.

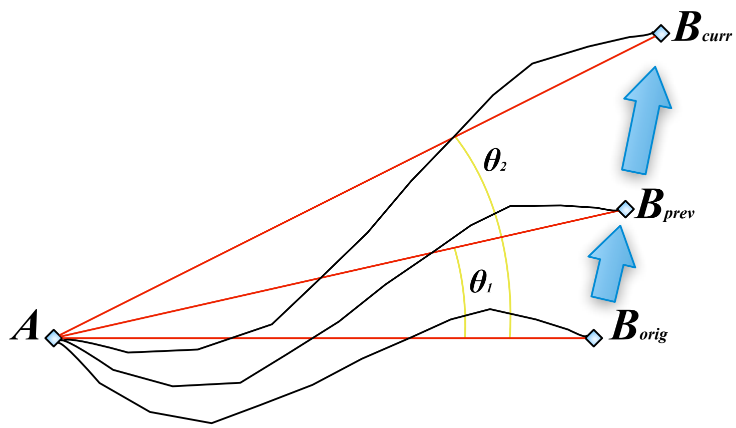

Figure 5. Illustration of the fabric stretch location correction algorithm, showing the various states of a corrected position *B* as it moves through positions B_{prev} to B_{curr}.

In our first implementation, we enabled correction that performed fabric stretch with a scope limited to the immediately previous and next Navcam positions neighboring the selected Navcam position. While this worked, the users found that for a very long path such as the first 5 years of positions of the Opportunity rover (many hundreds of Navcam positions and tens of thousands of intermediate points) that this was too tedious. We then extended the scope of the fabric stretch to travel backward and forward to wherever the nearest corrected Navcam position is, even if that means applying it to the entire path. We found that even when applied to data at this scale, the responsiveness of the interface did not suffer, and the gains in productivity are remarkable. With fabric stretch fully enabled, a geologist using the Map view was able to correct the entire 5 years (at that time) of Opportunity traverse locations in about 4 hours. The Map view has since been used on a day-to-day basis in MER operations and allows map corrections to be performed in just 2-3 minutes early on in the tactical timeline such that it can provide optimal information for traverse planning to the science team and the rover drivers right at the very beginning of their discussions.

C. Dynamic Overlaying

There are often areas where a Mars rover or lander takes multiple stereo images of the same areas of the surface, sometimes from the same position and other times from nearby positions. Landers obviously do this as a matter of course. Rovers frequently capture many overlapping images of major surface features that are very interesting or challenging to traverse (or both) such as the sloped walls of craters or other interesting geologic features such as Home Plate at Gusev Crater. In order to display all of the stereo image mosaics (such as Navcam for MER) in areas such as these, special attention was paid to optimizing rendering of a large number of images to maintain efficient performance. Without this attention, a naive approach that merely draws every Navcam mosaic when viewing regions of heavy Navcam coverage such as Opportunity's descent into Victoria Crater makes the display undesirably slow and unresponsive. The reason for this is of course a scaling problem: the cost associated with rendering each image with each update of the view (as the user pans or zooms the map) carries a cost. The key in optimizing away this problem lay in identifying the redundancies in the mutual coverage of neighboring Navcam mosaics and rendering only the images that are necessary and ignoring those that aren't.

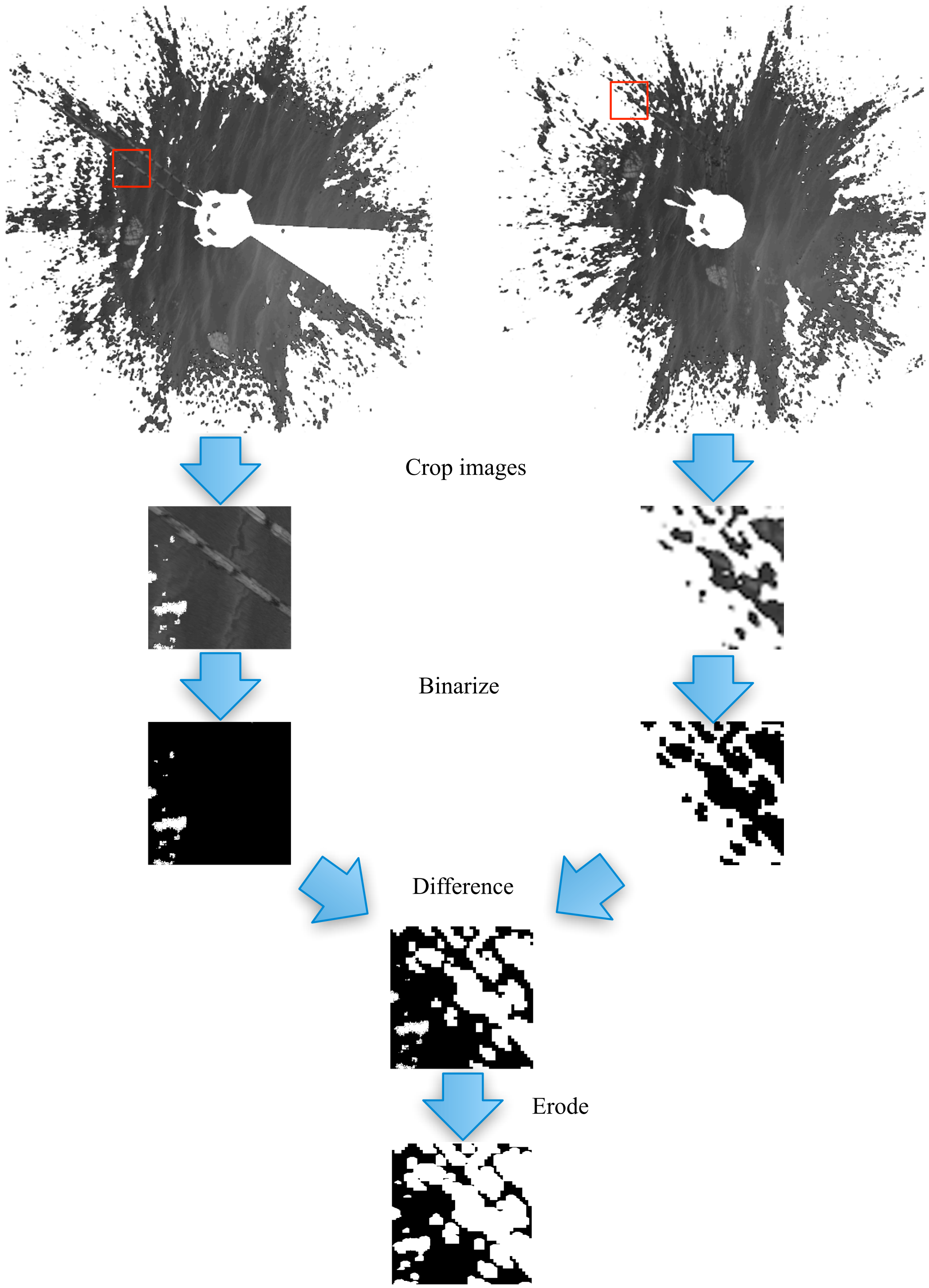

Figure 6. Flowchart of the dynamic mosaic overlay image processing pipeline.

In order to determine where there are Navcam mosaics that overlap each other we first set up a quadtree spatial data structure, encoding in it the bounding boxes of each mosaic. For any bounding boxes that intersect another box, there is a potential overlap. However, because the mosaics are circular rather than square and because they sometimes do not contain a full 360 degree coverage of imagery, overlapping bounding boxes do not guarantee overlapping images. To perform an accurate overlap test, we need to compare the images. We then set up an image processing pipeline to compare two candidate mosaics for overlap. We actually perform the overlap test not on the entire mosaic at once, since as mentioned in the previous section we render each mosaic from a series of tiles. Thus, we compare two overlapping tiles to determine whether they contain overlapping images. As shown in Fig. 6, we consider tiles from each of the two mosaics whose bounding boxes overlap in the quadtree. The areas containing no Navcam data are shown as white in the example images. We binarize each of the pixels of the two tiles, converting any pixels that contain valid data to black. We then perform an image subtraction on the two tiles, producing a difference image that contains black pixels that are not present in the image that we have already drawn. If there are sufficient black pixels in the tile that we have not yet drawn that are not present in the tile that we have drawn, we should draw this tile in order to add the additional pixel coverage, otherwise we can safely ignore the tile. Sometimes, there are only a few small, scattered areas of black pixels that add no real value to the map, so we perform a final image erosion operation to remove very small regions of black pixels. If there are black regions that remain after erosion then we render the tile on the map to add its data, otherwise we skip over it to gain performance. This image processing pipeline is efficient enough to run in the Map view interactively provided that the results are cached. For areas of heavy coverage, it is noticeably costly to run the pipeline at each rendering of the map, so we cache the results of the tile comparisons as they are computed and reuse those results until the cache becomes invalid either through interaction (such as bringing an obscured mosaic forward to render on top of the others) or through the introduction of new mosaics that are loaded over the network.

GIS

Geographic Information Systems or GIS is the field of geologic mapping that is accomplished with advanced software tools that are designed for that purpose. There are many GIS tools that are used in the study of geography of Earth, the moon and the planets. Perhaps the most universally known modern GIS tool is Google Earth. Like its companion web application Google Maps, Google Earth is a powerful visualization tool that brings together geographic information from disparate sources and displays them in a common context. Recently this application added a Mars GIS feature that allows its community to view geographic information from various missions such as HiRISE, the Mars Orbital Camera (MOC), the Thermal Emission Spectrometer (TES) and some of the panoramas from the MER rovers and Phoenix lander. The team at NASA Ames and Google who provide this application and its datasets provided a traverse path dataset that was created manually without the aid of the Maestro Map view. The long-term planning lead of the Athena Science Team for Spirit has created an improved traverse path dataset for Google Mars that has been scheduled for adoption as of this writing. A comparison of the traverse paths is shown in Fig. 7. In the figure, the original path is shown in red and the improved path is shown in yellow. As can be seen in the image, the improved path contains a point set of higher fidelity and has the benefit of many more corrected locations. The traverse dataset uses the KML standard for geographic data interchange and is also useful in other GIS tools such as ESRI ArcGIS that also supports this standard. Importing the traverse data into more powerful tools such as ArcGIS allows users to co-register the data with any Mars data in the historical data archive rather than be limited to only what is available in Google Mars.

IV. Conclusion

The Maestro Map view and its innovative work in localization correction for geologic mapping has made significant impact on MER rover operations. Our first result of significance was in testing the application with a geologic mapping expert at the controls. Our expert was able to perform accurate localization correction of five years of Opportunity rover Navcam traverse locations in about 5 hours of work. The system was sufficiently effective that it has now been adopted into the MER tactical planning process for Opportunity. With each downlink the Map view is updated with the latest traverse data and Navcam stereo imagery. At the beginning of the tactical planning timeline our expert user corrects the current rover position on the map and provides this information to the rover drivers to assist them in planning the next traverse for the rover to execute. This new paradigm of traverse planning in the context of a HiRISE map is an evolutionary step forward in the safety and efficacy of rover operations.

Apart from its enabling of improved operations, the Map view provides significant gains in Martian geologic mapping for the entire Mars science community. This new tool for determining accurate localization for rover locations puts the collective scientific data archive of the rovers into a better co-registered geologic context than ever before. The traverse datasets that have been delivered to Google Earth will provide this information to the international science community and also to the general public. The Map view is also now part of the baseline activty planning subsystem for the Mars Science Laboratory mission that is set to begin in 2011 where the tool can continue to make a significant contribution to our learning about Mars.

Shortly following the introduction of the Map view into MER operations there came feedback from the user community about the desire for a 3D interactive version of the map browser. We have begun working on this capability and we will soon publish a follow-on paper to this work that documents our experience to date in this rich and challenging area.

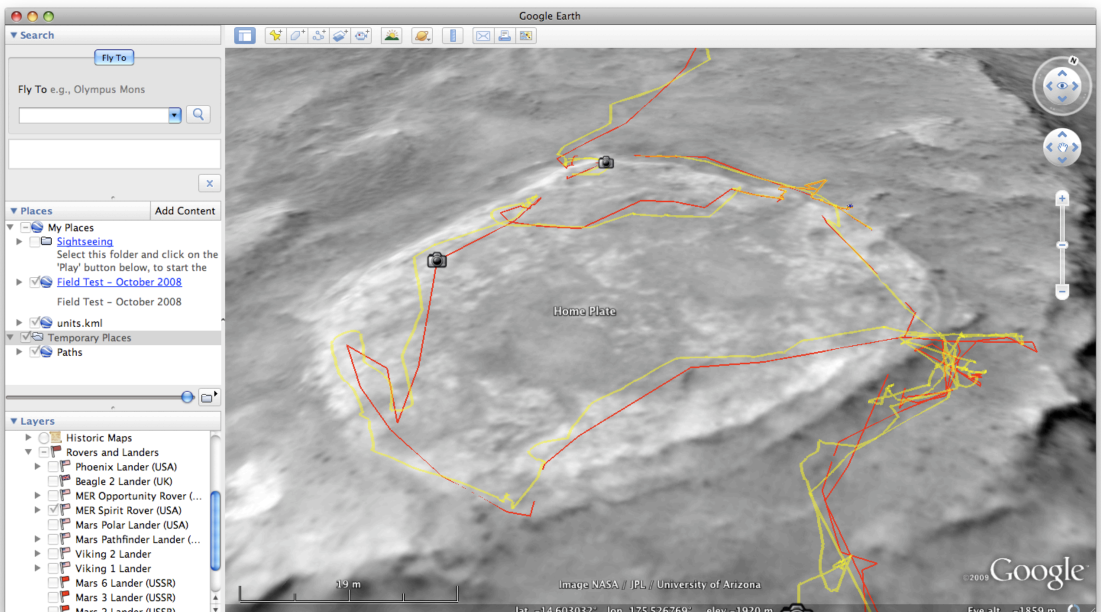

Figure 7. The Google Earth application viewing Home Plate at Gusev Crater with the Spirit Rover traverse path overlaid. The original path is shown in yellow and the improved path in red.

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