NEW PHOTOGRAMMETRIC TECHNIQUES USED IN THE 2003 MARS EXPLORATION ROVER MISSION

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ABSTRACT

The 2003 Mars Exploration Rover (MER) mission rovers, Spirit and Opportunity, have been exploring the Martian surface for more than two years (as of February 2006). During the mission, our team has routinely performed topographic mapping and rover localization to support strategic and tactical traverse planning as well as various scientific investigations. Topographic maps and localization data have been provided to MER mission scientists and engineers through a web-based GIS. This paper presents new photogrammetric techniques that are being used for the latest mapping- and localization-related activities. Among them is a bundle adjustment-based rover localization technology that has corrected wheel slippage, IMU (Inertial Measurement Unit) drift and other navigation errors as large as 10.5% in the Husband Hill area of the Gusev Crater landing site (Spirit) and 21% in Eagle Crater at the Meridiani Planum landing site (Opportunity). Detailed 3D terrain models of major features, such as Endurance Crater and Larry's Lookout, have been generated using multi-site or single-site panoramic stereo images. These models are being used as important data for geological analysis of craters and stratigraphy. Special products such as a north-facing slope map and a solar energy map have been generated to aid in choosing north-facing slopes where the Spirit rover can capture more solar energy during the upcoming winter season. Comparison of bundle-adjusted rover locations with those seen from orbital images is also being conducted to verify the bundle adjustment results.

INTRODUCTION

After landing on the Martian surface in 2004 (on January 4 and 25, respectively), the twin Mars Exploration Rover (MER) rovers, Spirit and Opportunity, have been exploring the landing sites of Gusev Crater and Meridiani Planum for more than two years. As of February 8, 2006 (Spirit's Sol 747, Opportunity's Sol 727, where a sol is a Martian day), Spirit has traveled 5.86 km and Opportunity has traveled 6.31 km (actual distances traveled, not odometry measurements). Localization of the rovers and mapping of the surrounding area are of fundamental importance to understanding where the vehicles have traveled and how to get them to new locations (Arvidson et al., 2004; Li at al., 2004, 2005a). During the MER mission, The Ohio State University (OSU) team, in collaboration with the Jet Propulsion Laboratory (JPL) and other institutions involved, has been routinely producing topographic maps, rover traverse maps, and updated rover locations to support tactical and strategic operations. These maps and localization data have been provided to MER mission scientists and engineers through a web-based GIS (Web GIS). The initial results of mapping and rover localization have been reported previously in Li et al. (2004, 2005a, 2005b, 2006) and Di et al.

(2005). These maps and localization information haven been used daily for traverse planning and have also been used in various scientific investigations by mission scientists (Squyres et al., 2004; Arvidson et al., 2004; Grant et al., 2004; Crumpler et al., 2005).

The rover localization and topographic mapping technology is based on the bundle adjustment (BA) of an image network formed by ground imagery, i.e., Pancam (Panoramic Camera) and Navcam (Navigation Camera) stereo images. The overall technology is described in Li et al. (2004) with some technical details explained in papers by team members (Di et al., 2004, 2005; Xu, 2004; Xu et al., 2005). In this paper, we present new photogrammetric techniques that are being used for the latest mapping- and localization-related activities. New products include detailed 3D models of major features generated from multi-site or single-site panoramic stereo images, special products such as a north-facing slope map and a solar energy map, and the drive metrics. Comparison of bundle-adjusted rover locations with those seen from MOC NA (Mars Orbiter Camera Narrow Angle) images is also presented.

ROVER LOCALIZATION

Rover Localization Techniques and Products

At the Gusev Crater site, localization of the Spirit rover has been performed sol by sol based on incremental bundle adjustment using full or partial Navcam/Pancam panoramic images and, occasionally, forward- and backward-looking Navcam/Pancam middle point survey images. Overall, after BA, 2D accuracy is sub-pixel to 1.5 pixels and 3D accuracy is at a centimeter to sub-meter level (based on consistency check of the BA results). On the overall traverse up to Sol 698, the maximum accumulated difference between the telemetry-derived traverse and the bundle-adjusted traverse is 66.60 m on Sol 525, or 1.6 percent of the distance of 4038.97 m traveled from the landing point, with a maximum of 2.7 percent (20.62 m over 775.70 m) on Sol 106.

Starting from Sol 154, we performed a local comparison of rover traverses where Spirit experienced significant wheel slippage climbing the Husband Hill area. Figure 1 shows the local comparison of bundle-adjusted traverse (red) and the telemetry-derived traverse (blue) from Sol 154 to Sol 698. The relative error reached 10.5% on Sol 337 (56.49 m accumulated difference over a distance of 540.88 m traveled since Sol 154), while the maximum accumulated difference is 82.06 m on Sol 648 (5.3% of traveled distance of 1539.40 m) at a location close to the summit. This demonstrates that the BA was able to correct significant localization errors as large as 10.5% at the Gusev Crater site.
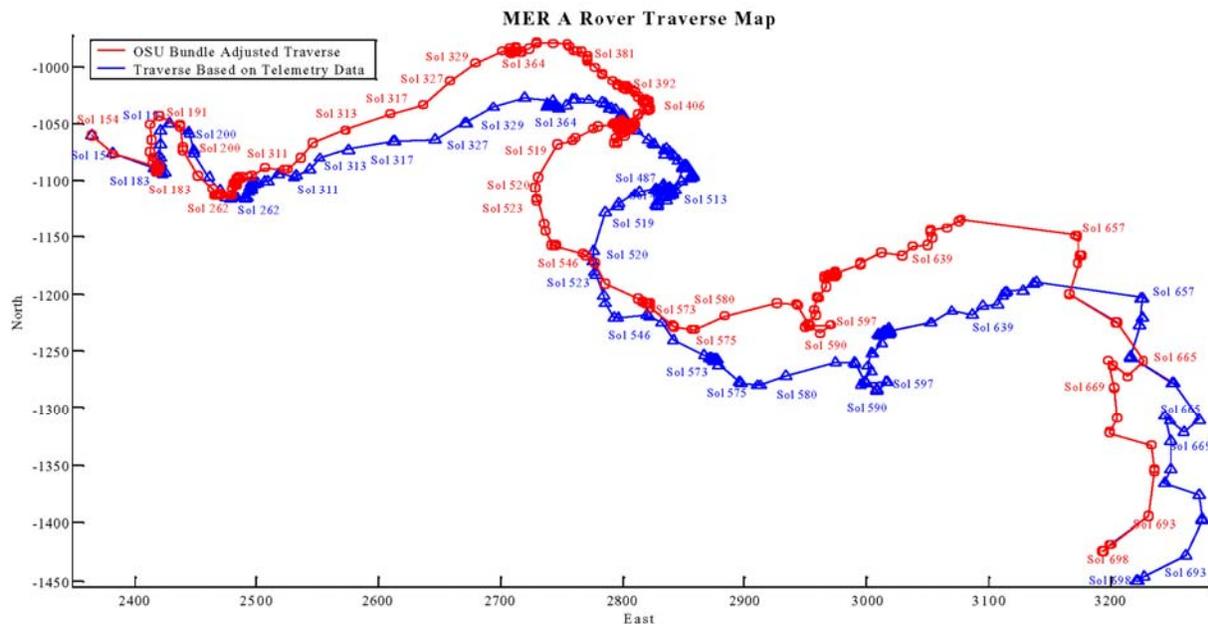

Figure 1. Spirit rover traverse from Sol 154 to Sol 698 (blue from telemetry; red from bundle adjustment).

To illustrate the terrain relief along the rover traverse, a vertical profile was generated and expanded as Spirit rover continued its traverse. Figure 2 shows the Spirit vertical profile from Sol 154 to Sol 698. The horizontal axis of the figure is the traveled distance, and the vertical axis depicts elevation (scaled). Again, the blue line is the profile computed from telemetry data and the red line shows the BA result. The accumulated elevation difference is 19.2 m over a traveled distance of 2.1 km. This difference may be attributed to wheel slippage and IMU (Inertial Measurement Unit) drift.

Based on the BA results, whenever there is a drive, we produce a rover traverse map. Figure 3 is the Spirit traverse map up to Sol 718, which shows the bundle-adjusted rover traverse overlaid on a MOC NA base map with of sol numbers and large features labeled.
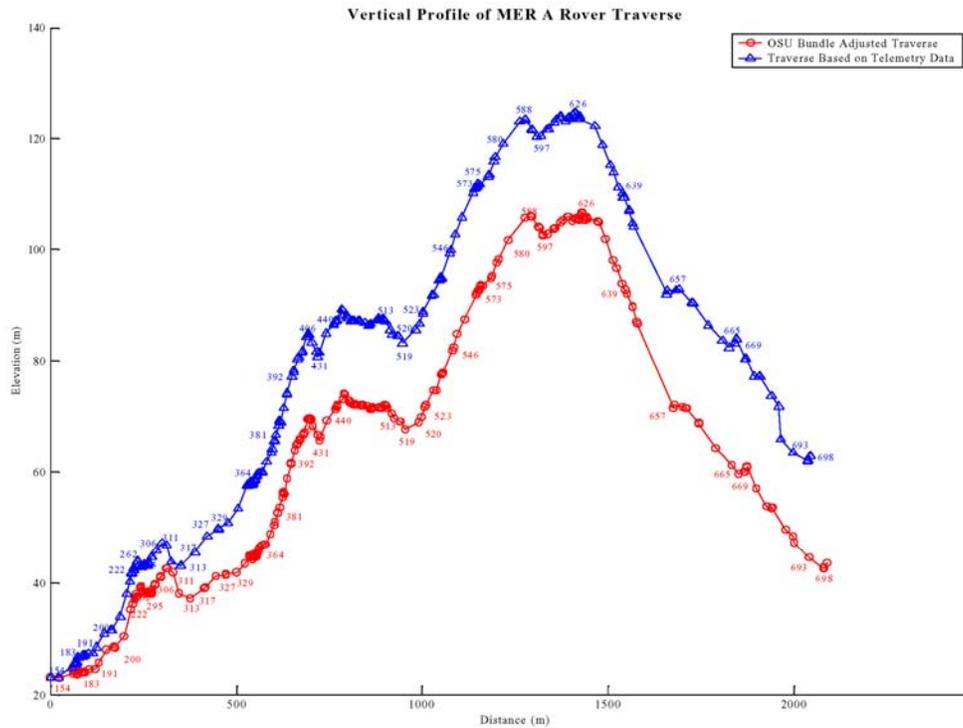

Figure 2. Vertical profile of the Spirit rover traverse (Sol 154 to Sol 698).
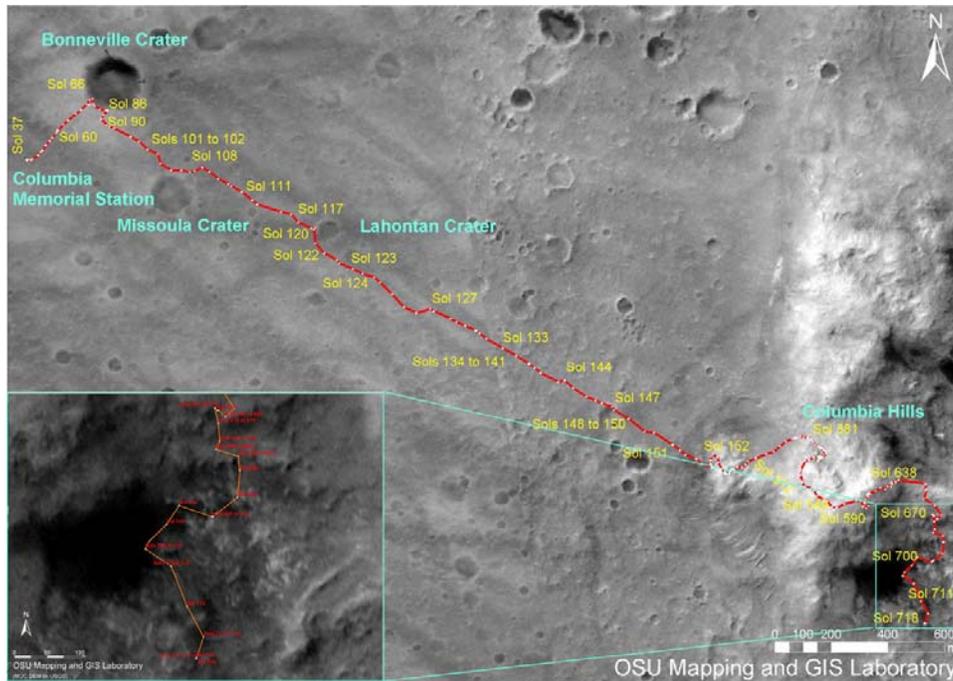
Figure 3. Spirit rover traverse map up to Sol 718.

On Sol 650, the science and engineering teams planned a long-term traverse to a large feature called Home Plate (see Figure 12), which is 848 m south of the rover's location on Sol 650. The targeted arrival date is Sol 740. In order to plan the daily drive efficiently, that is, to ensure that the rover arrives at Home Plate on time while still making sufficient stops to perform detailed investigation of interesting features along the way, it is important to monitor the rover's driving progresses towards Home Plate and to compare the actual drive with the targeted drive. For this purpose, we produced a drive metric every day as shown in Figure 4. The horizontal axis of the figure is sol number, and the vertical axis depicts accumulated driving progress. We can see that on most sols the actual drive (blue) is behind the targeted drive (red), indicating that more drives are needed to reach the destination in time. At the lower-right part of the figure, the necessary average drive distances per sol for the remaining sols are also listed. The drive metric and the traverse map (Figure 3) have been very helpful in daily traverse planning.
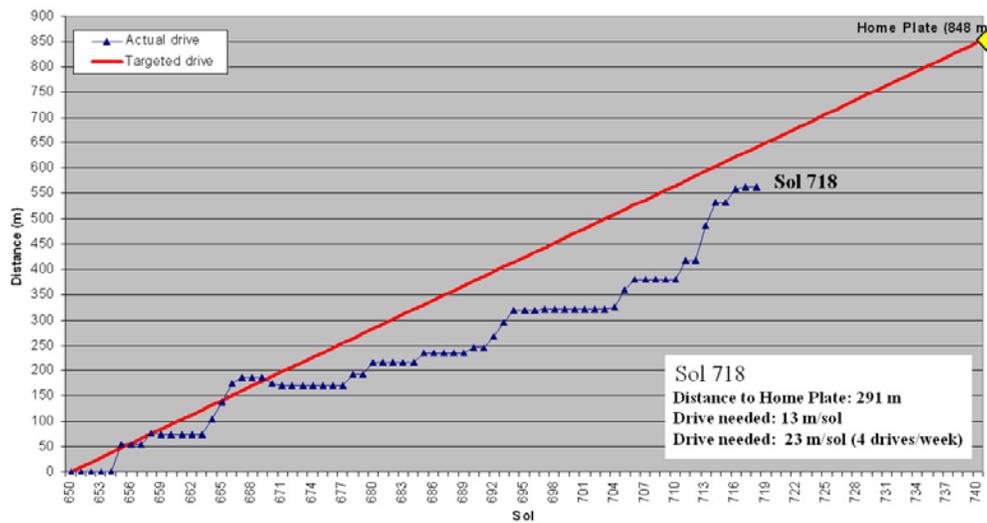

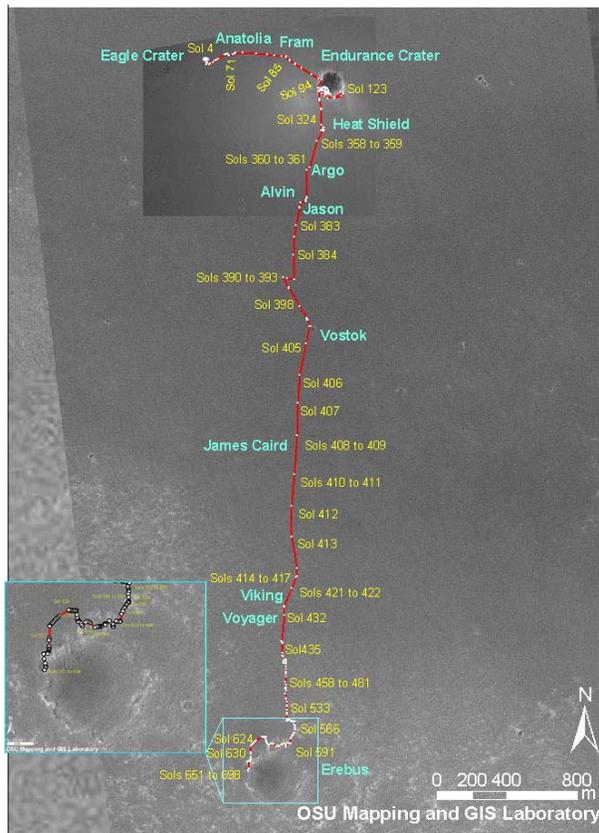**Figure 4.** Spirit drive metric to Home Plate (from Sol 650 to Sol 718).

Figure 5. Opportunity rover traverse map (up to Sol 698).

For Opportunity rover at the Meridiani Planum site, we conducted BA up to Sol 62 within Eagle Crater (where the rover Opportunity landed). The BA was able to correct a localization error as large as 21% that was caused by wheel slippage (Li et al., 2005a; Di et al., 2005). After leaving Eagle Crater, BA-based rover localization was impossible due to insufficient localization image data. Wherever we observed large features such as the Fram, Endurance, Argo, Jason, Naturaliste and Vostok craters, we generated orthophotos of these features and compared them with the MOC NA base map to adjust the rover traverse. Figure 5 shows the Opportunity traverse map up to Sol 698. Though not optimal, this adjustment strategy enabled us to provide the Opportunity traverse in a timely manner to support operations.

Comparison of Bundle-Adjusted Spirit Rover Locations and Rover Locations Seen on Orbital Imagery

On March 30, 2004 (Spirit's Sol 85) and August 18, 2004 (Spirit's Sol 223), MSSS (Malin Space Science Systems) acquired two MOC NA images showing Spirit's track on the images (Malin, 2005). We used the 1 m-resolution mosaic of these two images (MSSS release No. MOC2-960) to compare the track with the bundle-adjusted Spirit rover traverse (Figure 6). The shape and scale of the bundle-adjusted traverse and the track on the MOC NA mosaic match well. Howev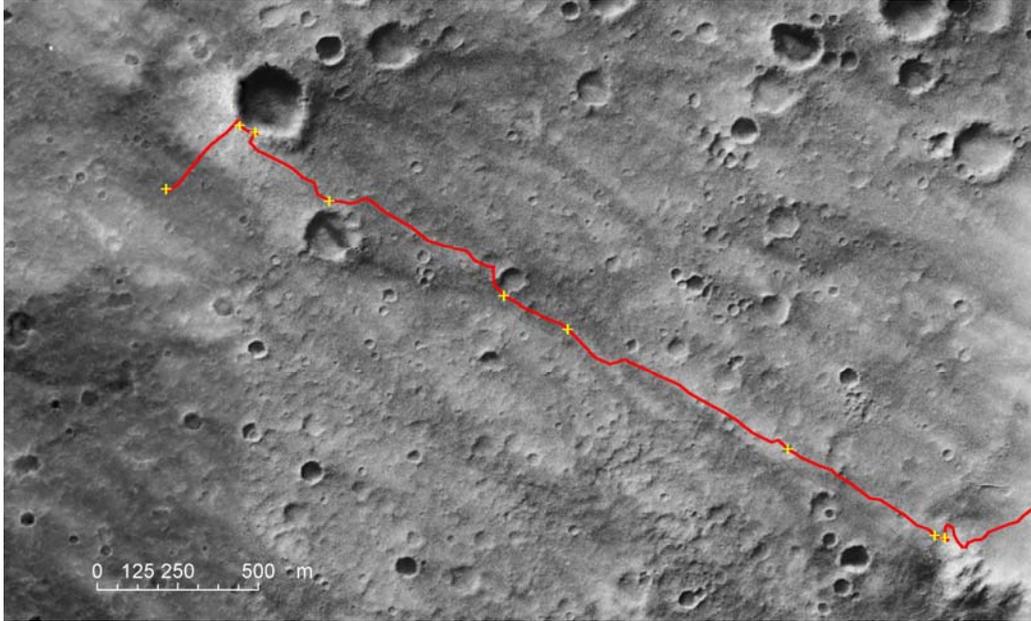er, there is a relative rotation difference of 1.3 degrees. A large part of this difference may be because the MOC mosaic of the image strips was "uncontrolled", i.e., the imaging geometry was computed solely from the pointing information of the orbital telemetry without any further 3D photogrammetric processing.

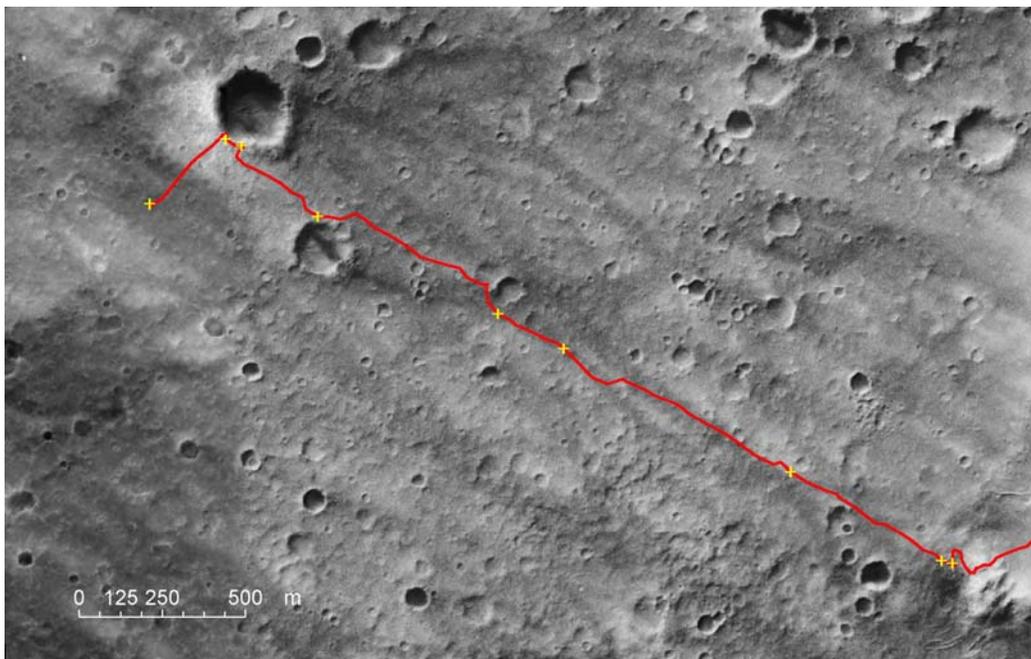**Figure 6.** Bundle-adjusted rover traverse on the MOC NA mosaic.

Figure 7. Bundle-adjusted rover traverse on the georeferenced MOC NA mosaic.

In order to make further comparisons, we georeferenced the MOC NA mosaic to the bundle-adjusted rover traverse using nine corresponding rover locations as control points (yellow crosses on Figure 6 and Figure 7). After georeferencing, we translated the MOC NA mosaic so that the two lander locations were exactly the same. Figure 7 shows the bundle-adjusted rover traverse overlaid on the georeferenced MOC NA mosaic. The rover track and the bundle-adjusted rover traverse now match very well. The difference between the two rover tracks at the last point (rightmost yellow cross) is 12 m (about 0.4 percent of traveled distance of 3081 m from the lander), while the average

difference at the nine locations is 8.8 m. Overall, this relative comparison shows the inconsistency between the bundle-adjusted rover traverse and the rover track on the MOC. This inconsistency is mainly caused by the georeferencing error of the MOC NA mosaic and the possible residuals of the BA.
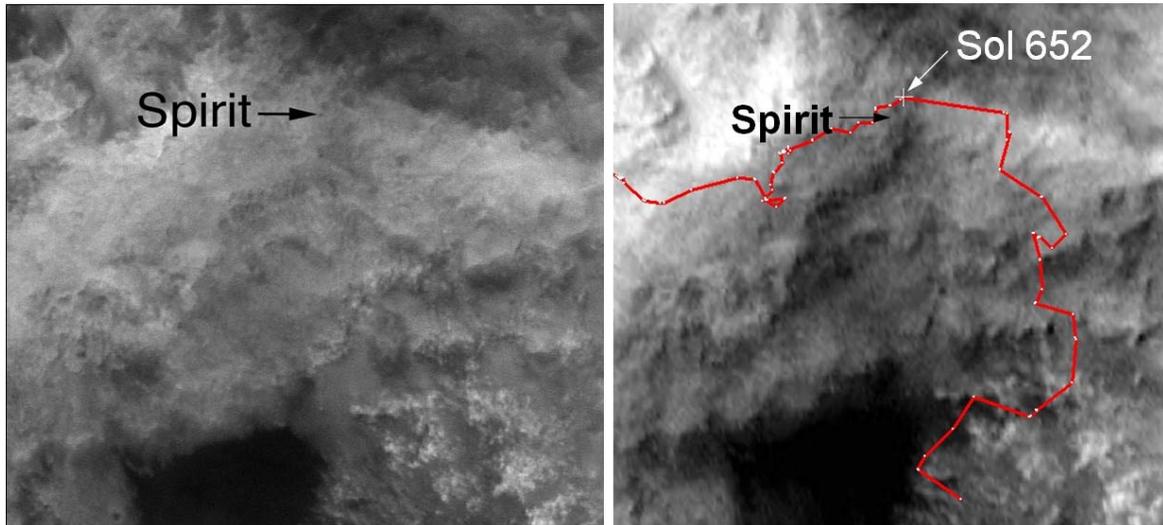

Figure 8. a) Another position of Spirit rover seen from MOC NA image,

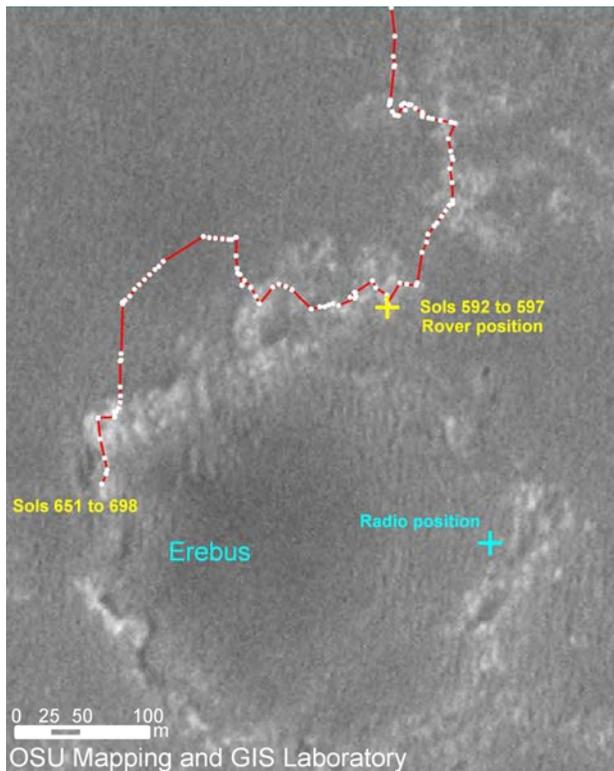b) Bundle-adjusted rover position on Sol 652 and the position transferred from a).

Figure 9. Adjusted Opportunity rover position and radio position.

On November 2, 2005 (Spirit's Sol 652), MSSS acquired another MOC NA image centered at the Husband Hill summit. Although the rover track is not visible, the rover itself was identified from the image (Figure 8a, Malin, 2005). We identified that position on our georeferenced base map according to surrounding features (Figure 8b). In comparing this MOC-imaged rover location with the bundle-adjusted rover position on Sol 652, a difference was found of about 20 m, or 0.4 percent of the overall traverse of 4559 m from the lander. It is important to note that this 20 m difference does not mean that the absolute accuracy of BA-based rover localization is 20 m. Again, this difference consists of the georeferencing error of the MOC base map and the residuals of the BA.

Comparison of Adjusted Opportunity Rover Location and Rover Location from Radio Tracking

In addition to image (ground and orbital) based rover localization, rover location can be determined through radio tracking. Results of radio tracking of the two lander positions have been reported previously (Parker et al., 2004; Li et al., 2005a). Figure 9 shows the radio tracking position and the adjusted Opportunity rover position (Sols 592-597). The differences between these positions are 78 and -186 meters in the East and North directions, respectively – a straight distance of 202 m. In comparison, the difference between the lander positions on the MOC NA base map and its radio tracking position is 140 m.

TOPOGRAPHIC PRODUCT GENERATION

By Sol 718 for Spirit and Sol 698 for Opportunity, we generated timely topographic products including 110 orthophotos and digital terrain models (DTMs), and six 3D crater and outcrop models. Most of the topographic products were automatically generated from single-site panoramic stereo images. For example, Figure 10 shows a DTM (a) and an orthophoto (b) of Larry's Outcrop that were generated from one partial Pancam panorama taken by the Spirit rover. Both the DTM and the orthophoto have a resolution of 5 mm. These maps served as fundamental data for stratigraphy analysis of the outcrop.
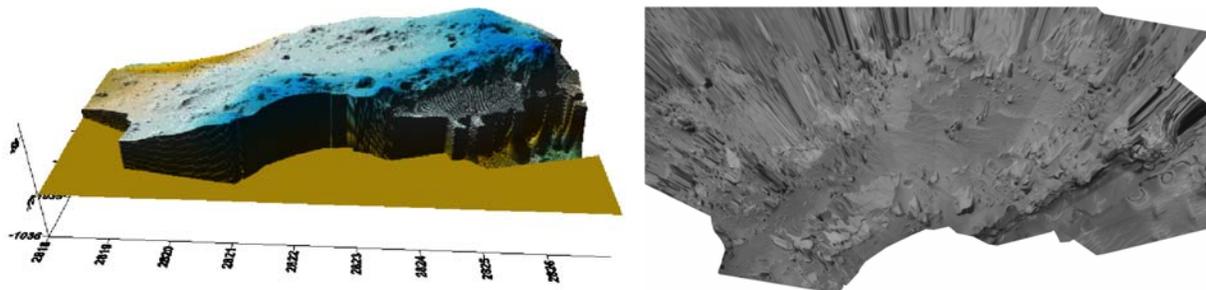

Figure 10. a) 3D view of DTM of Larry's Outcrop,   b) Orthophoto of Larry's Outcrop.

Integrated Mapping Using Multiple Panoramas and Wide-Baseline Images

For large features such as Endurance Crater (156 m in diameter) at the Meridiani Planum landing site (see Figure 5), a single-site panorama is not sufficient for reliable mapping of the entire feature because of the low measurement accuracy for far-range terrain. A natural method for large-area mapping is use of integrated multi-site
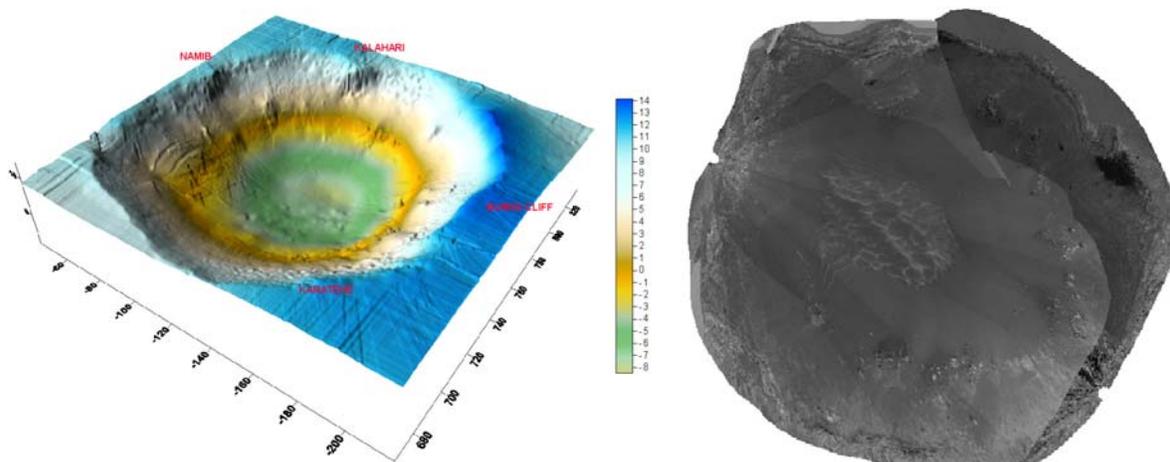

Figure 11. a) 3D view of the DTM of Endurance Crater,   b) Orthophoto mosaic of Endurance Crater.

panoramic images. The key to high-precision integrated mapping is bundle adjustment of all the relevant images to eliminate/reduce their inconsistencies. For Endurance Crater, we performed an integrated mapping using images taken at four rover positions: one stereo Pancam panorama from the west rim, another stereo Pancam panorama from the southeast rim, and two single Pancam panoramas taken at the bottom of the crater. The two single panoramas formed wide-baseline stereo pairs for 3D mapping. Initial mapping results using the two panoramas taken at the rim have been reported in Li et al. (2005a). The final DTM (with a resolution of 0.3 m) was generated using the all the images taken at these four positions. In addition, an orthophoto mosaic was generated from the two panoramas taken at the crater rim with the support of the integrated DTM. Figure 11a is the 3D view of the final DTM and Figure 11b shows the orthophoto mosaic. These maps, along with derived contours and vertical profiles,
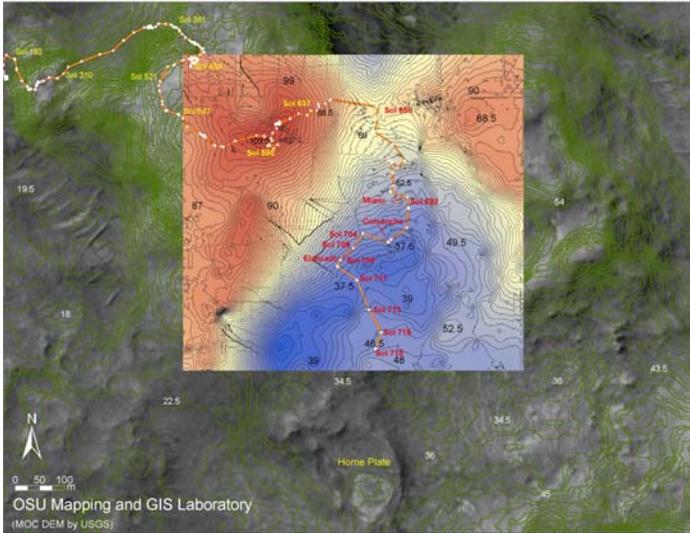
Figure 12. Topographic map of Husband Hill summit, inner basin, and Home Plate.

have been extensively used by mission scientists in detailed geological analysis of the crater.

At the Gusev Crater site, an integrated DTM was generated and expanded using multiple Navcam and Pancam panoramas (including wide-baseline) taken from Sol 576 to Sol 696 at the Husband Hill summit and the within the south inner basin. Figure 12 shows DTM and contours (central part, 690×640 m) of this area on top of a MOC NA base map along with contours derived from a USGS DTM. This map and its many previous versions were very helpful in planning the traverse to the summit and towards Home Plate through the east ridge.

Special Topographic Products

At the Gusev Crater site, we also produced special topographic products including a north-facing slope map and a solar energy map that were both computed based on the DTMs. The north-facing slope map (Figure 13) depicts the terrain slopes only in the north-south direction. In the figure, south-facing slopes are negative and north-facing slopes
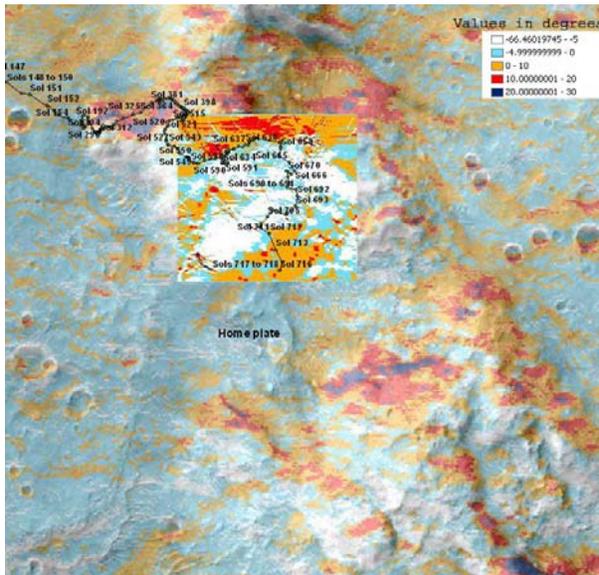

Figure 13. North-facing slope map of Husband Hill summit, inner basin, and Home Plate.

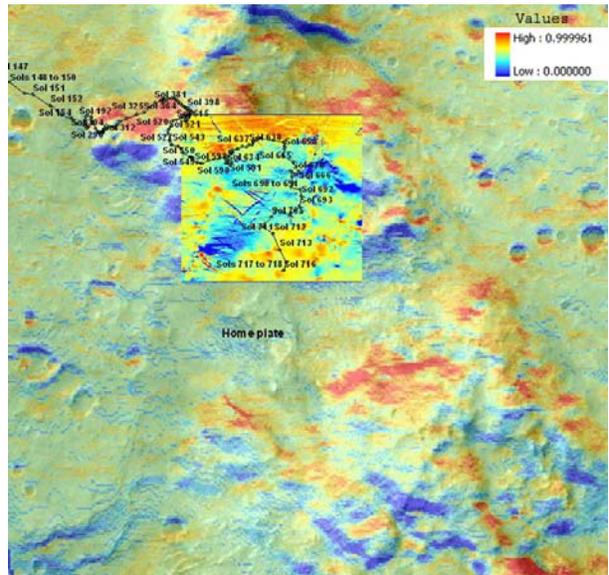**Figure 14.** Solar energy map of the area in Figure 12.

are positive. The solar energy map (Figure 14) is the dot product of the sun illumination vector and the local normal vector (north-south direction). The solar vector parameters are provided by USGS. The maximum value is 1, denoting the areas where the rover's solar panels would be perpendicular to the sun illumination vector and thus able to obtain maximum energy. These maps have been very helpful for picking rover traverse areas where the Spirit rover can capture more solar energy in the upcoming local Martian winter.

SUMMARY

This paper presents new photogrammetric techniques and the most recent topographic mapping products and rover localization results of the Mars Exploration Rover (MER) mission. The results demonstrate that BA-based rover localization continues to be able to correct significant rover location errors caused by wheel slippage and IMU drift. The rover localization data, routinely generated topographic products, and special products have been regularly used by the MER science and engineering teams for daily traverse planning as well as various scientific investigations.

At the time of writing (early February, 2006), both rovers continue to explore the two landing sites. We will perform topographic mapping and rover localization in support of the mission operations.

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