AUTOMATIC MARS LANDING SITE MAPPING USING SURFACE-BASED IMAGES

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ABSTRACT:

This paper presents techniques for automatic mapping of Mars landing sites using surface-based images, i.e., those taken by Mars landers and/or rovers. An innovative method for automatic tie point selection is presented that includes five steps: interest point extraction, interest point matching, parallax verification, graph consistency verification and final tie point selection with gridding. In matching interest points between adjacent stereo pairs, a rough DEM is generated to predict the location of conjugate points and to limit the search range. As a result, a surface image network is built by linking all the lander and/or rover images with the automatically selected tie points. An integrated bundle adjustment is developed and applied to the image network in order to improve accuracy of the position and orientation of the images as well as the ground location of feature points. Finally, a landing site DEM and a seamless orthophoto are generated using a set of automation techniques. The developed method and software are tested using lander images obtained from the 1997 Mars Pathfinder mission and rover images obtained from a 2002 FIDO test.

1. INTRODUCTION

High-precision topographic information is crucial to the achievement of scientific goals in Mars landed exploration missions as well as for engineering operations. In particular, large scale landing site mapping will be extremely important for future missions such as the 2003 Mars Exploration Rovers (MER), the European Beagle 2 Lander of the 2003 Mars Express, the 2009 Smart Lander and Long-range Rover, and return lander missions in 2010 and beyond.

Currently, before landing USGS MDIMs with a resolution of 231m are available. Viking images with a resolution of 40m can be employed. For future landing sites existing MOC and MOLA data are available. New orbital data may be acquired to support the selection of the landing sites according to both science objectives and engineering constraints.

During and after landing, ground-based "imagers" provide detailed images of the site. For example, Mars Pathfinder (MPF) mission’s lander imager IMP (Imager for Mars Pathfinder) acquired over 16,500 lander images and the rover Sojourner acquired 550 rover images (Golombek et al., 1999). These ground-based (lander and rover) images provided powerful close-range information to support micro-scale rock investigation, soil research and other scientific objectives. They supplied landing site information in unprecedented detail, much greater than that available in orbital images from previous missions such as the Viking 1 and Viking 2 missions or even the current Mars Global Surveyor (MGS) mission.

The methods used to derive topographic information from ground images are extremely important to the resulting topographic accuracy. For MPF IMP images, the USGS carried out photogrammetric and cartographic processing of the IMP images and produced a variety of topographic products including spectral cubes, panoramic maps and other topographic data (Gaddis et al., 1999; Kirk et al., 1999). A bundle adjustment was performed to revise the pointing data of the IMP images. Pointing errors of the raw IMP images are at least 5 pixels and are commonly as large as 15 pixels. After the bundle adjustment, the RMS residual between the measured image coordinates and the calculated ground points projected back into the image space is about 0.5 pixel (Kirk et al., 1999). The German Space Agency (DLR) has produced a multispectral panoramic image map and an orthoimage map of the MPF landing site by using similar photogrammetric and image processing techniques (Kuschel et al., 1999).

Since 1998, the Mapping and GIS Laboratory at The Ohio State University and the NASA Jet Propulsion Laboratory's Machine Vision Group have been jointly developing a bundle adjustment method with relevant techniques for the processing of Mars descent and surface images for rover localization and landing site mapping. In order to verify our algorithm and software, field tests were conducted at Silver Lake, CA in April 1999 and May 2000 (Li et al., 2001; Ma et al., 2001).

Based on the data obtained, various rover localization experiments were carried out. Using descent and rover images along with either an integrated or an incremental adjustment, rover localization accuracy was reached of approximately 1m for a traverse length of 1km from the landing center (Li et al., 2001; Ma et al., 2001). In addition to using simulated descent and rover images, we tested our methods and software with actual Mars data. We have reported the intermediate results of landing site mapping and rover localization from IMP data (Di, et al, 2002; Xu et al., 2002).

In this paper, we present techniques for automatic Mars landing site mapping using surface-based images and the final results of IMP data processing. Also, we report on the results of our landing site mapping from FIDO (Field Integrated Design Operations) test images obtained by the Athena Science Team in August 2002 in preparation of MER 2003 mission. The goals of our research are: 1) to enhance our bundle adjustment algorithm and software to achieve high accuracy and reliability and as well as flexibility in processing images from different lander/rover sensors, and 2) to automate the process of tie point selection and mapping product generation. This software will be used both to produce mapping products and to localize rovers during the MER mission.

2. IMAGE DATA

In this paper, we focus on our mapping efforts in automation of panoramic image processing and bundle adjustment. We use two sets of surface imagery to verify our algorithm and software. The first is MPF IMP lander images. We downloaded IMP images from the PDS (Planetary Data System) web site. The German Aerospace Center also provided us with a complete panorama chosen from a vast amount of IMP images. We selected 129 IMP images (64 stereo pairs and one single image) that form a 360º (azimuth) panorama. The footprints, image IDs, and Sols of the images are shown in the poster (last page). The tilt angle for the upper panorama ranged from 69~90º and the tilt angle for the lower panorama ranged from 50~69º. Overlapping exists in both the vertical and horizontal directions.

The second data set is from the Athena Science Team's FIDO test conducted in August 2002. In this test, the rover traversed about 200m in 20 Sols, taking more than 960 Navcam and Pancam images and collecting much other data. Some of the collected Navcam and Pancam images are panoramic. We select a 360º Navcam panorama at Site 5 to test our software and report the result in this paper. Figure 1 show the coverage of the images. Figure 2 is a rough mosaic of the images. We are currently adding additional Navcam and Pancam panoramic images along with traversing images to test the mapping and rover localization capabilities of our methodology.

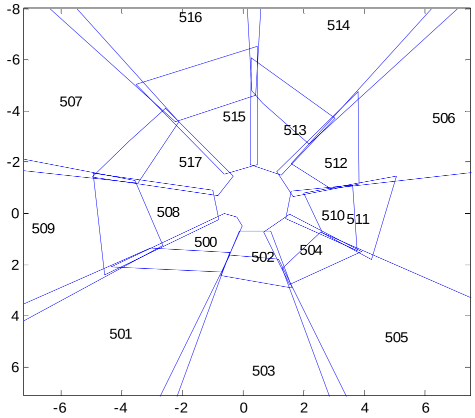

Figure 1. Coverage of Navcam images used in the experiment

Figure 2. A rough mosaic of the Navcam panoramic images

3. METHODOLOGY, PROCESSING AND RESULTS

Surface images are taken by lander/rover stereo cameras in Mars exploration missions. Intra-stereo images are stereo images that are taken simultaneously by left and right cameras linked by a "hard" baseline. These images will have a large area of overlap. Images taken at different times and linked through "soft" baselines to form stereo images are called inter-stereo images. Inter-stereo images have only a small area of overlap (e.g., 10%). Errors in the initial orientation parameters can cause inconsistencies between images and may lead to gaps between sections of DEM. To generate seamless DEM and orthophoto, orientation parameters must be adjusted to suppress any inconsistencies (Kirk et al., 1999, Li et al., 2001).

The process of landing site mapping consists of several steps: 1) tie point selection to build the image network, 2) bundle adjustment to improve the accuracy of image orientation parameters and ground coordinates, 3) DEM generation, 4) and orthophoto generation.

3.1 Automatic Selection of Tie Points

In order to build a geometrically strong image network and ensure the success of bundle adjustment, a sufficient number of well distributed tie points must be extracted and selected to link all the surface images to be processed. Automation of tie point selection will greatly reduce the amount of tedious manual work and thus speed up the map production process.

Tie points are selected from matched interest points. First, interest points are extracted using a Förstner operator (Förstner and Guelch, 1987). Then, area-based matching is applied to these interest points to find conjugate points. Typically, around 90% of interest points can find matches in an intra-stereo pair. However, there are often some mismatched points within the matched points. Next, the matched points are verified based on the consistency of parallax. To prepare an even distribution of tie points for later use in the bundle adjustment and for improvement of computational efficiency, the final selection of tie points is made from the verified matches using a gridding scheme. Figure 3 shows an example of automatically selected intra-stereo tie points.

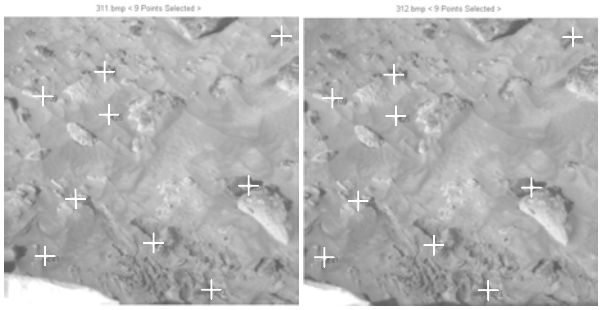

Figure 3. Intra-stereo tie points in IMP images

The matching of interest points between inter-stereo pairs is much more difficult because overlapping between the image margins is very small and disparities can often be very large. We use a coarse DEM to assist in finding correspondence between inter-stereo images.

Once the interest points from intra-stereo pairs are matched and verified, we calculate the 3D ground coordinates using the initial orientation parameters converted from the telemetry data. The 3D ground points are then used to interpolate a coarse DEM. With the coarse DEM, we can predict the overlapping of inter-stereo images. In addition, we can predict for an interest point the approximate location of its conjugate point in its corresponding inter-stereo pair image. This strategy works well for the adjacent stereo pairs of IMP and FIDO panoramic images. The matched points are verified using the parallax consistency method and final inter-stereo points are selected using a gridding scheme. Figure 4 shows an example of automatically selected inter-stereo tie points. More technical details of the automatic tie point selection method can be found in our recent publications (Xu et al., 2002; Di et al., 2002). Ultimately, selected intra- and inter-stereo tie points build an image network. The link map of the entire IMP panoramic image network is shown in Figure 5. Strong links (more than four pairs of evenly distributed tie points) are illustrated by solid lines and weak links (fewer than four pairs) by dotted lines.

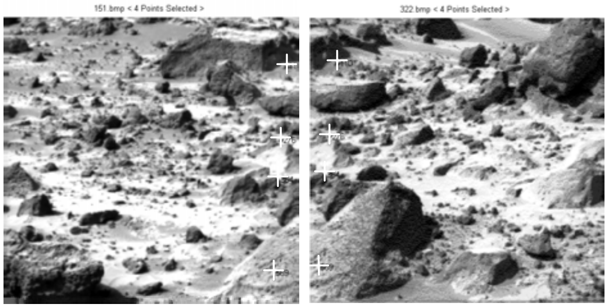

Figure 4. Inter-stereo tie points of IMP images

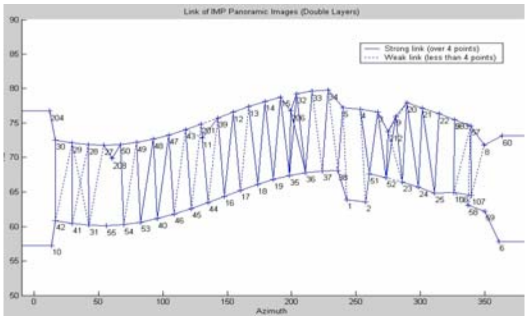

Figure 5. Link map of the IMP panoramic image network

Figure 6 shows an example of tie points automatically selected from FIDO Navcam images. Blue crosses are intra-stereo tie points and red crosses are inter-stereo tie points.

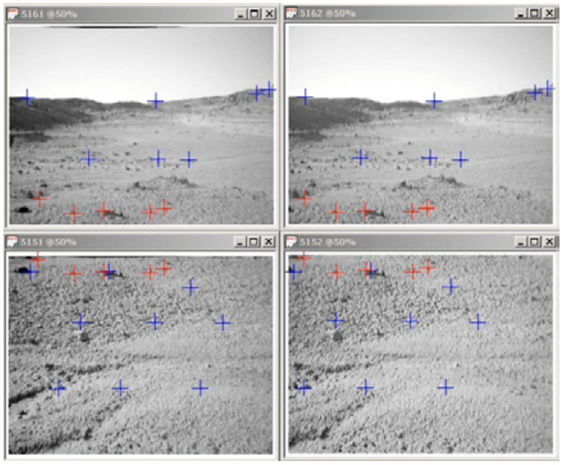

Figure 6. Automatically selected tie points from Navcam images

It should be noted that in some cases, especially where there are significant differences in illumination and/or sun angle, some tie points still need to be selected manually. Our experience processing IMP and FIDO panoramic images indicates that over 95% of tie points can be automatically selected.

3.2 Bundle Adjustment

Bundle adjustment of the image network is the key to improving mapping accuracy and the accuracy of rover localization. We have developed algorithms and software for both integrated and incremental bundle adjustments (Li et al., 2001; Ma et al., 2001; Di et al., 2002).

IMP lander images have some special characteristics. For example, estimated camera motion and position and, in particular, camera positions and attitudes, are strongly correlated because of the fixed stereo camera bases between the left and right cameras and the rotation around the IMP vertical axis. A complete set of constraint equations has been derived to model the unique geometric characteristics of the stereo cameras. The bundle adjustment software has been extended to incorporate these constraints to provide high-precision exterior orientation (EO) parameters of the images as well as ground positions of the tie points. For the FIDO data set, because the detailed calibration results are not yet available to us, we are still working on constraint issues. In the following experiment we conducted bundle adjustment of FIDO images without constraints.

There are several frames of reference that are used in the MPF image pointing data, including the camera head coordinate system, lander (L) frame, Martian Local Level (M) frame, Mars Surface Fixed (MFX) frame, and Landing Site Cartographic (LSC) coordinate system. Bundle adjustment and topographic products of IMP data are based on the LSC system as defined by the U.S. Geological Survey.

We developed a program to convert the pointing data of the PDS images to the exterior orientation data. This is accomplished by a chain of translations and rotations through the above frames of reference. Converted exterior orientation values were then used as initial values in the bundle adjustment.

For the FIDO data, the WITS (Web Interface for Tele-Science) system has converted the original telemetry data to CAHV and CAHOVR models. We developed a program to convert the CAHV and CAHOVR models to the conventional photogrammetry model that consists of interior orientation parameters, lens distortion parameters, and exterior orientation parameters. Bundle adjustment and topographic products of FIDO data are based on a local coordinate system defined by the Athena Science Team.

Since there are no absolute ground checkpoints, we have used the following three methods to evaluate the precision of the bundle adjustment. 1) 2D residuals of back-projected tie points: bundle-adjusted 3D coordinates of tie points in the object space are back-projected to the stereo images. The back-project points are compared with their corresponding points to produce differences that are used to assess the precision. 2) 3D differences of inter-stereo tie points: after bundle adjustment, the adjusted orientation parameters can be used to triangulate points in the object space. For checkpoints in inter-stereo overlapping areas, the 3D position can be triangulated from the left and right inter-stereo pairs. Differences in their 3D coordinates from the left and right stereo pairs are calculated and compared. 3) 2D differences of inter-stereo tie points: similar to method 2, for a tie point in the left pair we triangulate the 3D position and then back-project it to the right pair. The back-projected point is then compared with the corresponding tie point in the right pair image. In all three methods, the averages of absolute coordinate differences are calculated to depict the precision.

The entire IMP panorama consists of 129 images that form either an upper panorama and a lower panorama with horizontal links, or an entire panorama with both horizontal and vertical links (see Fig. 4). In the image network, there are 655 tie points, 633 of which are automatically selected and 22 that have been manually selected. A comparison of precision before and after adjustment is listed below.

Method 1 using 694 checkpoints, average image differences:
    (3.00, 2.70, 4.61) pixels in (x, y, distance) before adjustment
    (0.58, 0.41, 0.80) pixels in (x, y, distance) after adjustment
Method 2 using 655 checkpoints, average ground differences:
    (0.040, 0.046, 0.028) meters in (x, y, z) before adjustment
    (0.030, 0.036, 0.018) meters in (x, y, z) after adjustment
Method 3 using 655 checkpoints, average image differences:
    (6.58, 5.46, 9.57) pixels in (x, y, distance) before adjustment
    (1.10, 0.75, 1.49) pixels in (x, y, distance) after adjustment

From this comparison, we can see that precision is improved in image space and object space by the bundle adjustment, with the improvement in image space being more significant. Overall, accuracy after the adjustment is around 1 pixel in the image space and 3 cm in the object space.

In the FIDO data processing, a panoramic image network is built by linking 36 Navcam images (18 pairs) at Site 5 with 249 automatically selected intra- and inter-stereo tie points. Before adjustment, the precision is 3.36 pixels in the image space (distance between measured and back-projected image points from Method 1) and 0.26 meter in the object space. After bundle adjustment, the precision is 0.74 pixel in the image space and 0.10 meter in the object space. Thus precision has been improved in both image and object space.

3.3 DEM Generation

After bundle adjustment, a high-precision DEM is generated using the following steps: 1) build a Triangular Irregular Network (TIN) from matched and verified interest points that are selected at a 50 cm interval, 2) initialize a grid DEM with the TIN using the Krigging method, and 3) refine the grid DEM by back-projecting each grid point to the two stereo images. A matching process is then applied to find the actual elevation of the grid point. This process continues until all the grid points are calculated as an elevation. The final refined DEM of the MPF landing site is show in the poster in the last page. Figure 7 shows the final DEM of the FIDO site in 2D grayscale and 3D perspective view.

3.4 Orthophoto Generation

The orthophoto is generated by back-projecting the grid points of the refined DEM onto the left image. A corresponding grayscale value is found and assigned to the grid point. In the area of overlap for adjacent images, the grid points will be projected to two or more images. The grayscale value is picked from the image in which the projected point is closest to its image center. Figure 8 shows the orthophoto of the FIDO site. Through visual checking, we find no seams between image patches. This demonstrates the effectiveness of the bundle adjustment.

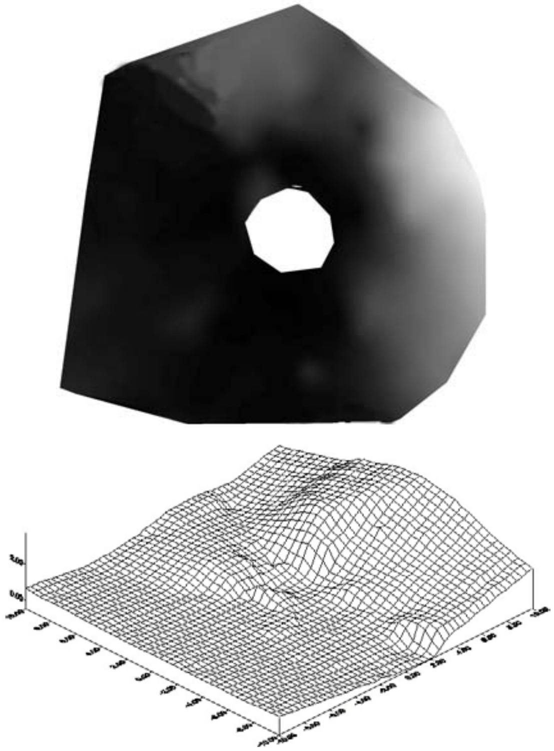

Figure 7. DEM of the FIDO site

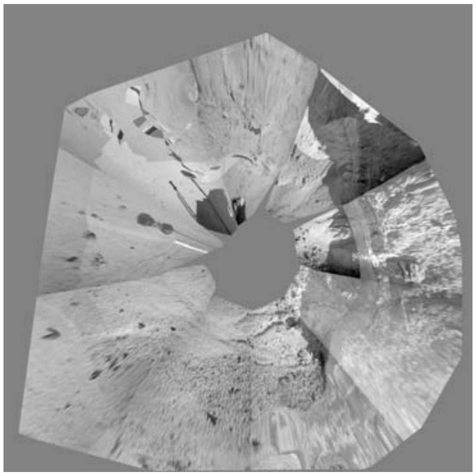

Figure 8. Orthophoto of the FIDO site

The orthophoto and a 3D view of the MPF landing site are shown in the poster in the last page.

We compared our IMP orthophoto with the JPL mosaic map and the DLR orthophoto by measuring the ground coordinates of five rocks. The comparison shows that the points from our orthophoto are very close those from DLR.

We are currently processing additional FIDO Navcam and Pancam data to produce DEM and orthophoto of the FIDO site. The latest results will be presented at the workshop.

4. SUMMARY

In this paper, we present techniques for automatic mapping of Mars landing sites using surface-based images. We have report the results using MPF IMP images and partial results from incorporation of FIDO data. These results demonstrate that accuracy of the exterior orientation parameters of surfaces images has been improved by the bundle adjustment. Consequently the differences between measured image points and those back-projected from adjacent stereo images were reduced from several to over ten pixels to a sub- to one-pixel range. Our automatic tie point selection, DEM and orthophoto generation methods have been proven effective and efficient. We will finish processing the FIDO data, further enhancing our algorithms and software and making the software ready for use during the MER mission.

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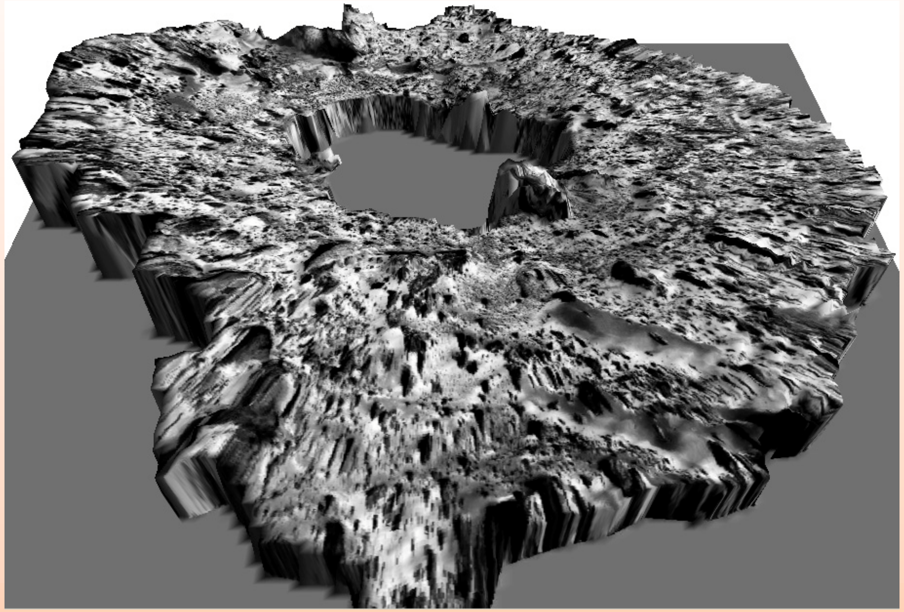
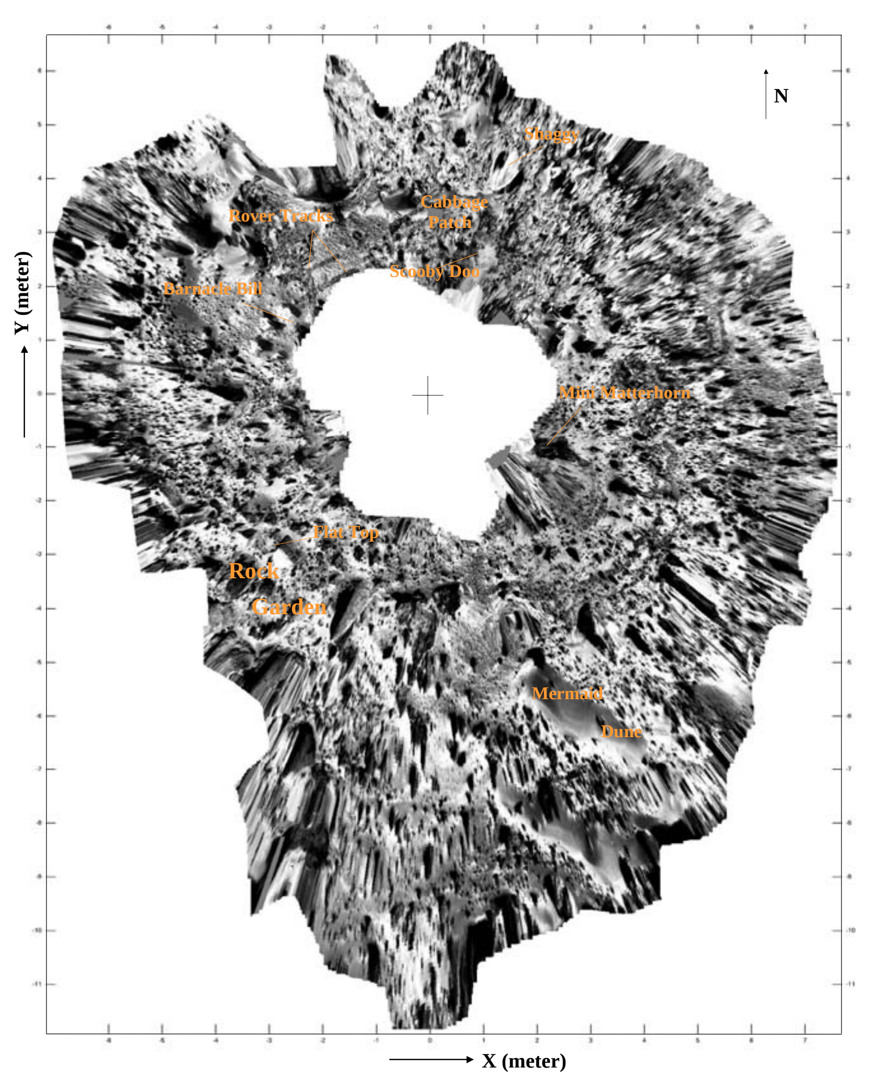
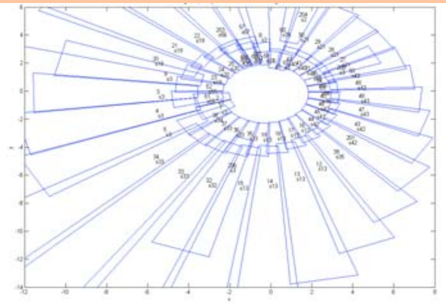
TOPOGRAPHY OF THE MARS PATHFINDER LANDING SITE



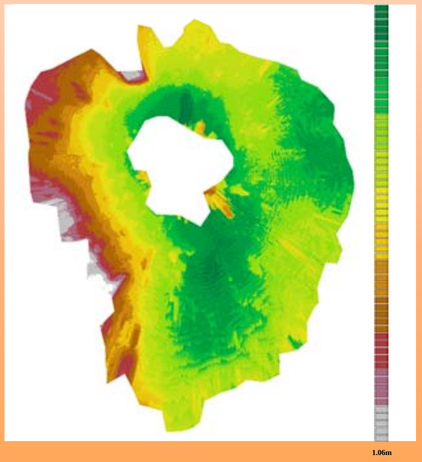
Orthophoto on DEM



Orthophoto



IMP images used



DEM

Data Sources:

IMP (Imager for Mars Pathfinder) stereo images from PDS (Planetary Data System)/NASA
IMP stereo images from DLR (German Aerospace Center)
A bundle adjustment of the images was performed at OSU
Collaboration with Dr. Larry Matthies of JPL and Dr. Clark Olson of University of Washington is acknowledged

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Department of Civil and Environmental Engineering and Geodetic Science
The Ohio State University

Principal Investigator: Dr. Ron Li

Researchers and contributors: Dr. Kaichang Di, Fengliang Xu, and Jue Wang

Reference Frame:

Landing Site Cartographic Coordinate System defined by USGS (US Geological Survey)