ULTRAHIGH RESOLUTION TOPOGRAPHIC MAPPING OF MARS WITH HiRISE STEREO IMAGES: METHODS AND FIRST RESULTS.

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Introduction: The Mars Reconnaissance Orbiter (MRO) arrived at Mars on 10 March 2006 and, after several months of aerobraking, began its primary science phase in November. The High Resolution Stereo Imaging Experiment (HiRISE) on MRO is the largest, most complex camera ever flown to another planet. Plans call for this scanner to image roughly 1% of Mars by area at a pixel scale of 0.3 m during the next Mars year [1]. Among the thousands of images will be ~1000 stereopairs that will provide an unprecedented three-dimensional view of the Martian surface at meter scale. In this abstract, we describe our approach to generating geodetically controlled digital topographic models (DTMs) from such stereopairs, our first results, and plans for future DTM production.

Image Characteristics: The HiRISE camera is characterized by high signal to noise ratio (SNR) and large image size in addition to high resolution. The focal plane contains a total of 14 CCD arrays, each of which operates as a 2048-pixel-wide line detector to build up an image in pushbroom mode, but with up to 128 lines of time delay and integration (TDI) to ensure a high SNR even in shadows and in the polar regions. The combination of high SNR, low compression, and excellent resolution of small features such as rocks leads, in most cases, to an abundance of surface detail that greatly facilitates stereomatching of the images.

Ten of the detectors, filtered to accept only red wavelengths, overlap slightly in the cross-track direction to provide continuous coverage of a swath 20,000 pixels wide. The wide image provided by the red detectors is of greatest utility for stereoanalysis, as well as for many morphologic studies. Additional detectors sensitive to blue-green and near-infrared wavelengths permit false-color imaging of the central 4000 pixels of the swath. The along-track length of images that can be acquired depends on the number of CCDs used, pixel binning (if any) and data compression, but can be as much as 80,000 lines at full resolution. At this size, a single HiRISE pair yields more topographic information than was contained in the entire global DTM of Mars that was produced by the USGS from Viking Orbiter images in the 1980s. Only the availability of digital or "softcopy" photogrammetric tools running on high-speed workstations make the generation of DTMs from such large images practical.

Small motions of the spacecraft around its nominal pointing ("jitter") will distort the images, a problem that was identified for Mars Orbiter Camera (MOC) images [2] but that is more severe for HiRISE because of its higher resolution. In addition, the distortions will occur at slightly different places in the images from different CCDs, complicating the assembly of the full image. This occurs because the detectors are displaced alternately forward and aft in the focal plane, so that they can overlap across-track to build up a continuous swath. The same feature therefore crosses the overlapping detectors at different times. In addition, because the reflecting optics of HiRISE obscure the central part of the field of view, the entire detector assembly sits slightly behind the optical axis. The slight (~0.5%) radial optical distortion of the camera therefore displaces features both along-track and across-track at the location of the detectors, so that the individual CCDs must be rotated by angles ranging from zero to 0.25° to ensure that ground features stay in the same detector column during the time delay integration. All of these factors (jitter, detector offsets, detector rotations, and optical distortion) must be and are taken into account during our reconstruction of the images in order to obtain precision cartographic products.

The stereo parallax generated by the along-track offset of the different detectors is negligible (~0.03°). Stereo coverage is therefore obtained by rolling the spacecraft to obtain a second image of a previously acquired target on a later orbit that passes nearby. For features at low latitude, such rolls provide a crosstrack stereobase that is within a few degrees of being east-west. At high latitudes, the situation is more complex; to image the pole, for example, the spacecraft must be rolled to the poleward side of its inclined orbit on both opportunities, and the stereobase is primarily horizontal and along-track. Targeting of stereopairs requires a complex tradeoff between optimal convergence angle (typically 20–25° but smaller angles are preferred for very rough terrain and vice versa), minimizing the delay between images to avoid surface changes and large shifts in illumination conditions, avoiding low phase angles (which yield low-contrast images that are difficult to stereomatch), and avoiding conflicts with other observations. An early goal of the HiRISE team is to gain experience about what imaging geometries and camera settings lead to acceptable stereopairs for both interactive viewing and DTM production.

Methodology: Our approach to the photogrammetric processing of HiRISE images follows that which we have previously described for the MOC and the Mars Express High Resolution Stereo Camera (HRSC) [2, 3]. In brief, we use the USGS in-house digital cartographic software ISIS to do initial processing, including ingestion, decompression, and radiometric calibration of the images [4]. "Three-dimensional" photogrammetric processing steps, including bundle adjustment for geodetic control, DTM creation by automatic stereomatching, and interactive quality control and editing of the DTMs, are performed on a photogrammetric workstation running the commercial software SOCET SET (® BAE Systems) [5]. Software written at the USGS translates the images and the supporting geometric metadata into formats that SOCET SET understands. Derived products, such as DTMs and orthorectified images (projected onto the DTMs), are translated back into ISIS format for further processing including mosaicking and scientific analysis.

Within this broad outline, two aspects of HiRISE processing deserve comment as distinct from our past efforts. In the past, images from MOC, HRSC, and many other planetary cameras were prepared for stereoanalysis by processing in the ISIS 2 system [6]. HiRISE is the first instrument to rely entirely on the object-oriented successor system ISIS 3 [7] for standard data processing, and thus the first for which we have created ISIS 3–SOCET data translators.

A more significant challenge was posed by the geometric complexity of the HiRISE camera. SOCET SET provides a "generic" sensor model (i.e., software that computes the transformation between image coordinates and ground coordinates) for pushbroom scanners, which we have successfully used for MOC and HRSC processing. Unfortunately, this model cannot be used to model raw HiRISE images at the level of accuracy required, because it does not allow the detectors to be located away from the axis of radial optical distortion. Rather than develop our own sensor model specific to HiRISE, we have elected to pre-process the images in ISIS to remove the optical distortion so that the existing sensor model can be used. The ISIS 3 program *noproj*, written for this purpose, transforms input images by projecting them into ground coordinates of latitude and longitude and then back into the image coordinates of an idealized, distortionless HiRISE camera that can be modeled in SOCET SET. Other geometric effects are corrected at the same time: data from the offset and rotated real CCDs are transformed to what a single, straight detector would have seen, so that they can be mosaicked together and treated as a single image. To the extent that the "jitter" motions of the platform are known, these can be corrected by *noproj* as well, so that the ideal image is what would have been seen from a more stable platform. We will return to the issue of jitter below.

"First Light"—Victoria Crater: The dataset selected for initial testing of our software and development of mapping procedures covers the 750-m crater Victoria in Meridiani Planum. The *Opportunity* rover arrived at Victoria in September 2006 and will ultimately descend into the crater to investigate the stratigraphic column it exposes, so a high resolution topographic model of the region is of great value to mission planners. We had previously generated a DTM (unpublished) at 5 m/post from ~1.5 m/pixel MOC images.

Images. Three HiRISE images of Victoria have been obtained and were processed: TRA_000873_1780 (0.267

m/pixel, 3.75° emission), PSP_001414_1780 (0.276 m, 17.54°), and PSP_001612_1780 (0.265 m, 1.95°). In all cases, the spacecraft is east of the crater. The expected vertical precision EP, assuming 0.2 pixel matching error [2] is 0.22 m for a stereopair consisting of the first two images, and 0.19 m for the second and third image.

Control. For this project we treated the images from individual CCDs (after *noproj*) as independent. Only the two or three red detector segments that overlapped the crater were used; segments from each of the three HiRISE images were adjusted together. The ultimate source of control was the Mars Orbiter Laser Altimeter (MOLA) global DTM. MOLA has unprecedented absolute accuracy both horizontally and vertically [8], but the spot size, spot spacing, and DTM grid spacing are all in the hundreds of meters, making it challenging to identify corresponding features on the HiRISE images. We therefore used coordinates measured from the 1.5 m/pixel MOC images previously controlled to MOLA for horizontal control, ensuring that the two datasets would be registered to one another even more precisely than either is tied to MOLA. A total of 33 features within ~1 km of the crater were measured interactively: 5 with horizontal coordinates weighted at 10 m, 22 with heights weighted at 3–5 m, 1 with both, and 5 as tiepoints with no ground coordinates assigned. Most points were measured on 4 overlapping images, resulting in an average of 16 points per image.

Because of the narrow (~1°) field of view of HiRISE, it is neither possible nor necessary to adjust both camera position and pointing. We adjusted the spacecraft position (with a weighting of 1000 m along track, 100 m across track, and 10 m radially) and the rotation around the camera axis, (weighted at 0.02°) but held the remaining pointing angles fixed. Linear drifts of these parameters were also permitted. Spacecraft positions for all images moved consistently about 1000–1700 m along and 260 m across track, probably reflecting real errors in the reconstructed trajectory available to us. With a looser radial weighting, the spacecraft also moved up 500 m, which we believe to be the result of an along-track scale error. With the 10 m weighting, RMS residuals were 9.4 m in longitude, 26.5 m in latitude, 7.9 m in elevation, and 0.86 pixels in the images (line and sample errors combined). The horizontal errors with respect to the MOC base are disappointingly large compared to the MOC and HiRISE pixel scales, but it is clear that the two datasets are controlled consistently at a precision better than the ≥100 m accuracy with which either can be located relative to MOLA.

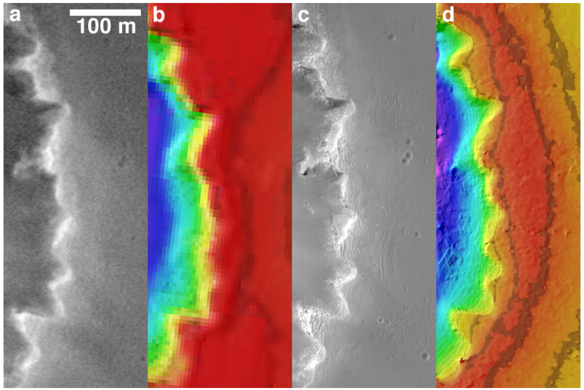

Figure 1. a) Part of the rim of Victoria crater, MOC image R14-00021 at 1.5 m/pixel, North up. b) Corresponding area of color shaded relief from manually edited MOC DTM at 5 m/post. c) HiRISE image PSP_001612_1780 at 0.3 m/pixel. d) Shaded relief from *unedited* HiRISE DTM at 1 m/post. Same color coding as b. Contour interval is 4 m, total range of elevations is 51 m.

DTM Generation. This first study area proved to be extraordinarily challenging for automated stereomatching. The Meridiani plains are extremely flat and covered primarily by fine material that appears featureless at HiRISE resolution [9]. Sedimentary outcrops and eolian ripples less than a meter high provide image texture in a few areas, but much of the region surrounding the crater is featureless apart from a scattering of small rocks and faint streaking with windblown dust. The interior slopes of the crater are similarly bland but relatively steep (up to 30°). Outcrops in the crater walls are vertical and many are deeply shadowed. We previously found it almost impossible to match images of the Meridiani plains at MOC resolution [2}, and resorted to interactive measurements to obtain the MOC DTM of Victoria. Despite these challenges, we obtained a useful DTM over most of the crater and surroundings by automatic matching of the HiRISE images PSP_001414 and PSP_001612. Results in bland areas were improved considerably by applying a difference-of-Gaussians (DoG) bandpass filter [10] to the images, followed by a contrast enhancement, for the final pass of the multi-resolution, multi-pass matching strategy. The high SNR of HiRISE permitted accurate matching within deep shadows, but the change in position of the shadow edges between images resulted in unavoidable artifacts. Small variations in the apparent height of the plains, caused by matching error, are at the sub-meter level, in agreement with the EP calculated above. Overall, the expectation of a substantial improvement in DTM detail from the 5-fold improvement in pixel scale relative to MOC is clearly fulfilled.

Future Work: Following delivery of DTMs of Victoria crater and the *Spirit* rover site in the Columbia Hills to the MER team, our next priority is the generation of DTMs in the candidate landing sites for the Phoenix mission. HiRISE images of the previously selected sites, which we mapped and found to have acceptable slopes at MOC resolution [11], showed a hazardous density of rocks. After an extensive reexamination of the target latitude zone, three new sites in the longitude range 235–255°E have been chosen [12]. The first stereopairs of these sites have recently been acquired.

Subsequent mapping will address the scientific priorities of the HiRISE team. Among the regions already identified as of greatest interest are young or potentially active features (gullies, high latitude flow lobes and crevasses, polar "spiders" and geysers, polar layered terrain, sublimation scallops in Hellas), stratigraphic sequences and contacts (layered deposits in Valles Marineris and craters, including Holden and Eberswalde deltas), tectonic features (faults in Candor Chasma), the freshest volcanic features (e.g., in Athabasca Valles), impact features (very fresh craters, possible secondaries), and past landing sites, where ground truth is available.

Technical objectives include finding the optimal combination of filtering and parameter values for the stereo matching software to produce detailed and artifact-free DTMs, streamlining the stereo processing as far as possible, in particular by working with mosaics of all *noproj*-corrected CCD images into a single large scene, reducing the number of control points to measure and DTM segments to manage. We will also experiment with using photoclinometry (shape-from-shading) to refine stereo DTMs by adding detail [3].

A final, important goal is to address the issue of spacecraft jitter in the images. By using the real (jittery) pointing of the spacecraft on input and an idealized smooth pointing history on output, *noproj* is capable of removing jitter distortions. Our preliminary tests indicate, however, that using the standard mission product for pointing (reconstructed SPICE CK files [13]) can introduce more errors than it removes, because the pointing angles in these files are coarsely quantized on the scale of several HiRISE pixels. The sampling of the standard kernels is also too slow to capture important motions of the spacecraft. We are therefore working on a process to reconstruct an improved pointing history from a combination of the standard CK file, special high-rate data from the spacecraft's gyroscopes, and information obtained by comparing the data from overlapping CCDs, which image the same feature at different times during the motion. Assembling these sources of data into an optimal estimate of the true pointing history will be challenging but will pay off in the form of more accurate DTMs without the "washboard" artifacts that can be introduced by jitter [2].

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