MAPPING MARS WITH HRSC, ISIS, AND SOCET SET. R. L. Kirk[1], E. Howington-Kraus[1], D. Galuszka[1], B. Redding[1], T.M. Hare[1], C. Heipke[2], J. Oberst[3], G. Neukum[4], and the HRSC Co-Investigator Team, [1]U. S. Geological Survey, Flagstaff, AZ 86001, U.S.A. (rkirk@usgs.gov), [2]Institute of Photogrammetry and GeoInformation, Univ. of Hannover, Germany, [3]DLR, Berlin, Germany, [4]Institute of Geological Sciences, Freie Universität Berlin, Germany.

Introduction: This abstract describes the techniques developed at the U.S. Geological Survey, Flagstaff, for stereomapping with images from the Mars Express High Resolution Stereo Camera (HRSC) and includes a preliminary characterization of the resulting products that we are preparing for a detailed comparison with products made from the same images by other instrument team members using other software. Although we use commercial software to produce digital topographic models (DTMs), a significant amount of the processing is done by using the USGS software system ISIS, which thus provides useful capabilities to potential users of HRSC data.

HRSC [1] is the first camera designed specifically for stereo imaging to be used in mapping a planet other than the Earth. Nine detectors view the planet through a single lens to obtain four-band color coverage and stereo images at 3 to 5 distinct angles in a single pass over the target. The short interval (tens of seconds) between acquisition of the successive images ensures that the surface, atmosphere, and lighting conditions will be unchanged, minimizing problems in comparing the stereo images. The resolution of the nadir channel is 12.5 m at periapsis, poorer at higher points in the elliptical orbit. The stereo channels are typically operated at 2x coarser resolution and the color channels at 4x or 8x. Since the commencement of operations in January 2004, approximately 51% of Mars has been imaged at nadir resolutions better than 50 m/pixel. This coverage is expected to increase significantly during the recently approved extended mission of Mars Express, giving the HRSC dataset enormous potential for regional and even global mapping.

Systematic processing of the HRSC images is carried out at the German Aerospace Center (DLR) in Berlin, by using the VICAR software system [2]. This processing includes decompression of the images, radiometric calibration, orthorectification (i.e., projection into map coordinates allowing for topographic parallax) based on elevations from MOLA altimetry [3], and production of standardized stereo DTMs and orthorectification based on these. The resulting standard products are referred to as Levels 1, 2, 3, and 4 respectively (note that these correspond to Levels 0, 1, 2, and 2 as generally referred to in ISIS processing [4]; ISIS refers to map-projected products as Level 2 regardless of the DTM data used for rectification). These products are generated systematically, in near-real time for all orbits, though only the HRSC Level 2 products are currently being archived. The tradeoff of universal coverage but limited DTM resolution makes the standard products optimal for many but not all research studies. Experiments on adaptive processing with the same software, for a limited number of orbits, have allowed DTMs of higher resolution (down to 50 m/post) to be produced [5]. In addition, numerous Co-Investigators on the HRSC team (including ourselves) are actively researching techniques to improve on the standard products, by such methods as bundle adjustment (i.e., controlling the images to improve registration with MOLA and other datasets), alternate approaches to stereo DTM generation, and refinement of DTMs by photoclinometry (shape-from-shading) [6]. The Photogrammetry and Cartography Working Group (PCWG) of the HRSC team is conducting a systematic comparison of these alternative processing approaches by arranging for team members to produce DTMs in a consistent coordinate system from a carefully chosen suite of test images.

DTM Comparison Tests: The comparison process consists of test images, specifications for products to be generated by test participants, and procedures for evaluation of the products. Two datasets have been chosen as the highest priority for initial comparisons. These are a single image set from orbit h1235 and a block of three adjacent images from h0894, h0905, h0927. The area of interest in h1235 covers western Candor Chasma (-8° to -4°N, ~282° to 284°E) at a nadir resolution of 27 m/pixel and includes the spectrally distinctive Ceti Mensa [7]. The second test area covers Nanedi Vallis (test area 7.5° to 12.5°N, 310° to 314°E) at 12 to 15 m/pixel. In addition to being scientifically interesting, this area provides a test of capabilities for producing seamless DTMs from blocks of images by bundle adjustment. Image sets of secondary interest that may be used for additional testing include h2138 (overlapping h1235 but with higher resolution and image quality), h0427 (western rim of Argyre), h1070 (Juventae Chasma), and h2101 (including both eastern Valles Marineris and chaotic terrain to the east).

Output products will be produced in IAU/IAG 2000 coordinates [8] with planetocentric latitude and east longitude. For simplicity, elevations will be referred to a sphere of radius 3396.0 km rather than to an equipotential system. DTM products are to be produced in sinusoidal projection with specified center longitude for each test area, but each test participant is free to choose an appropriate grid spacing. If possible, raw (ungridded) ground point coordinates from image matching as well as DTMs will be submitted for comparison. Products will be evaluated at the Univ. of Hannover and at DLR under the auspices of thePCWG and the ISPRS Working Group on Extra-terrestrial Mapping. Qualitative and quantitative criteria to be applied range from subjective evaluation of the fidelity with which DTMs portray features visible in the images to the density of matched points and statistical comparisons of the differences between elevations from HRSC and those from MOLA. HRSC DTMs may also be compared with DTMs derived from MOC-NA images, which have higher resolution but potentially include systematic distortions. The USGS database of MOC stereopairs [9] includes three useful pairs in the west Candor test area and one in the Nanedi Vallis area. Finally, the effort required to generate DTMs by different approaches will be compared.

Processing Approach: We have developed an independent capability for processing of HRSC images at the USGS, based on the approach previously taken with Mars Global Surveyor Mars Orbiter Camera (MGS MOC) images [10]. The chosen approach uses both the USGS digital cartographic system ISIS and the commercial photogrammetric software SOCET SET (® BAE Systems) and exploits the strengths of each. This capability provides an independent point of comparison for the standard processing, as described here. It also prepares us for systematic mapping with HRSC data, if desired, and makes some useful processing tools (including relatively powerful photometric normalization and photoclinometry software) available to a wide community of ISIS users.

ISIS [11] provides an end-to-end system for the analysis of digital images and production of maps from them that is readily extended to new missions. Its stereo capabilities are, however, limited. SOCET SET [12] is tailored to aerial and Earth-orbital imagery but provides a complete workflow with modules for bundle adjustment (MST), automatic stereomatching (ATE), and interactive quality control/editing of DTMs with stereo viewing (ITE). Our processing approach for MOC and other stereo datasets has been to use ISIS to ingest images in an archival format, decompress them as necessary, and perform instrument-specific radiometric calibration. Software written in ISIS is used to translate the image and, more importantly, orientation parameters and other metadata, to the formats understood by SOCET SET. The commercial system is then used for "three-dimensional" processing: bundle-adjustment (including measurement of needed control points), DTM generation, and DTM editing. Final steps such as orthrectification and mosaicking of images can be performed either in SOCET SET or in ISIS after exporting the DTM data back to it. This workflow was modified slightly for HRSC to take advantage of the standard processing performed at the DLR [2]. As the first step in DTM production, we use the ISIS program *mex2isis* to import Level 2 VICAR files into ISIS where they can immediately be used (e.g., orthorectified based on MOLA or other preexisting DTM data by using the program *lev1tolev2*) or exported to SOCET SET. HRSC Level 3 and 4 products can also be imported with *mex2isis* and used as map-projected data (e.g., Level 4 DTMs from DLR can be compared with those produced in SOCET SET).

The importation of Level 2 images includes reformatting needed to accommodate limitations of the ISIS and SOCET SET sensor models. HRSC scanner images can have different exposure times for different lines, as recorded in VICAR line prefixes, but the sensor models require a fixed exposure time. Blocks of consecutive lines with constant exposure time are therefore identified and formatted as separate ISIS images. One line of overlap is provided between successive blocks so that they can be tied together during bundle adjustment. If necessary, the blocks are split into files small enough to be compatible with operating systems using 32-bit addressing. SRC images, which are provided in various cropped formats, are padded out to a fixed size corresponding to the full detector array.

Preliminary Results: Our preliminary results for h1235, reported here, are encouraging even though the analysis did not take full advantage of the multiple-line design of HRSC. In our preliminary bundle adjustment we computed offsets to the trajectory and pointing angles for each image of the set as if they were fully independent, rather than requiring a single trajectory and pointing history versus time for all the images. In addition, the version of SOCET SET used (v 4.4) is limited to using only two images at a time in the stereo matching process. We are currently working to address these shortcomings (see below). Our bundle adjustment yielded RMS residuals of 3.6 pixels in the nadir image, correspondingly less in the other bands. RMS residuals to the ground control provided by MOLA were ~400 m (the MOLA grid spacing) horizontally but only 1 m vertically. Adjustments to the spacecraft orientation were surprisingly large, and may be correlated: 1 to 7 km in position, $\leq 0.2°$ in twist around the boresight, $\leq 1°$ in the other two angles. Placement of the (manually selected) control points was found to be critical; matching MOLA to the images to constrain horizontal coordinates is easiest at slope breaks such as the canyon edges, but vertical constraints are best obtained in areas of low rather than high slope. As a result, it is preferable to choose separate points for horizontal and vertical control.

We found it useful to collect DTMs at different resolutions in different areas (75 m/post in the canyon interior, 300 m on the walls and surrounding plateau), then resample them to the highest resolution and merge them. Editing was required only to remove a few localized artifacts on the plateau, which is nearly featureless and very difficult to stereomatch. As would be expected, the resulting DTM appears sharper than either MOLA at 463 m/post or the standard HRSC DTM at 200 m/post, and the added detail is subjectively well correlated with the image (Figure 1). The small DTM fluctuations in smooth areas, which do not correlate with features in the images, provide an estimate of the precision of stereomatching. The RMS amplitude of such fluctuations corresponds to 0.18 pixel (RMS of nadir and oblique pixel sizes) matching error, consistent with the usual "rule of thumb" of 0.2 pixel precision.

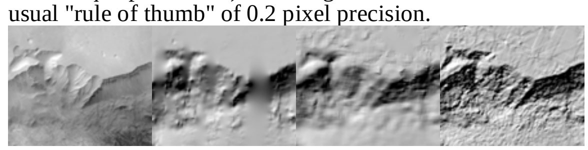

Figure 1. Portion of test area showing rim of Candor Chasma. L to R: HRSC image, shaded relief from MOLA (note interpolated gaps), DLR standard stereo DTM, and USGS stereo DTM.

We orthorectified the images and performed further processing in ISIS. Users without access to SOCET SET could use the standard DTMs or MOLA data to do similar processing, although the misregistration between image bands would be greater. Using the program *photomet* we simulated the surface shading appropriate to each image, which allowed us to correct for both topographic shading (as resolved by the stereo DTM) and the additive contribution of atmospheric scattering to each image. From the corrected images we then made color albedo maps, color ratio images, and (from the nadir and stereo channels) photometric phase ratio images. The albedo maps are not perfect; they contain localized artifacts because of the limited resolution of the DTM. By dividing the nadir image by a smoothed version of the albedo map, we were able to obtain an image in which albedo variations over distances of more than a few hundred meters had been removed. The albedo-corrected image was then analyzed by two-dimensional photoclinometry [13] to generate a DTM that contains real geomorphic detail at the limit of image resolution while retaining consistency with the stereo and MOLA data over longer distances. Without the albedo correction based on the stereo DTM such a result would be unachievable because of the extremely strong albedo contrasts in the test area.

Work in Progress: We are currently reprocessing h1235 and processing the Nanedi Vallis images in the agreed-upon coordinate system, with the images in each set constrained to move together during bundle adjustment, and with a new version of SOCET SET (v 5.2) that performs multi-way matching between sets of more than two images. Constraining the bundle adjustment should improve the accuracy of the result, and is expected to reduce the amplitude of the position and pointing offsets, which are likely to be highly correlated. Multi-way matching should yield a DTM with better accuracy, fewer artifacts, and fewer posts where matching fails altogether and the height is merely interpolated from nearby values. We will show the products from this improved processing in our poster, characterize the improvement resulting from the revised processing, and report initial results from the DTM comparison effort that pertain to the USGS products.

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