RESULTS FROM MULTI-STRIP BUNDLE ADJUSTMENT WITH HRSC IMAGERY J. Bostelmann (bostelmann@ipi.uni-hannover.de), C. Heipke, Institute of Photogrammetry and GeoInformation, Leibniz Universität Hannover, Nienburger Str. 1, D-30167 Hannover, Germany

Introduction: More than 12 years ago the European Space Agency (ESA) sent its first interplanetary mission to our neighboring planet: Mars Express was launched on June 2nd, 2003 and inserted into orbit around Mars on December 25th that same year. One of the scientific instruments on board the orbiter is the High Resolution Stereo Camera (HRSC). This multi-line sensor with five panchromatic and four multi-spectral CCD arrays was developed by the German Aerospace Center (DLR) and specifically designed for photogrammetric mapping purposes.

The HRSC images the Martian surface with a resolution of up to 12m per pixel. The along-track multi-stereo capability of the camera delivers image strips with three-dimensional information, which cover nearly the whole planet. The different observation angles of the panchromatic channels allow photogrammetric object point determination in each recorded image strip. Four additional channels provide color information in red, green, blue and near infrared. For a derivation of accurate digital terrain models (DTMs) and orthophotos the geometric accuracy of the available orientation data (position and pointing) of the camera is improved via bundle adjustment. This non-linear least-squares optimization uses a large number of image tie point observations to adjust the camera orientation parameters. The derived DTMs and orthophotos are regularly released to NASA's Planetary Data System (PDS) and ESA's Planetary Science Archive (PSA) and are used by a large number of scientists, e.g. for geological analysis [1].

Method: With the beginning of a systematic mapping of Mars, the United States Geological Survey (USGS) divided the Martian surface into 30 tiles. This Mars Chart 30 (MC-30) tiling scheme is now also used for photogrammetric mapping with HRSC imagery. Because of gaps in the coverage and for reasons of computational efficiency in the current processing strategy the MC-30 tiles (except for the polar tiles) are split into two halves. These MC-30 half-tiles define the boundaries for the generation of large DTMs [2] and orthophoto mosaics [3]. To ensure a seamless fitting the HRSC image strips of each half-tile are combined to photogrammetric blocks, thus allowing a simultaneous adjustment of the different strips. Compared to the adjustment of individual strips, a block adjustment reduces not only local, but also regional inconsistencies of the data, like displacements between neighboring strips.

Because of the highly elliptical orbit of Mars Express, the geometric properties of the image strips, e.g. size and resolution vary widely, and so do the illumination directions. Furthermore the image quality is occasionally degraded by haze and sandstorms, and by oscillations of the spacecraft during image acquisition [4]. Thus, the data set of HRSC strips for each block is very heterogeneous and the **selection of suitable strips** is an essential first step of the whole workflow [5]. The next step, the **tie point matching** takes place in four substeps:

- initially a Gaussian filter is applied to all HRSC images in order to remove image noise and compression artefacts.
- 2. To reduce geometric differences in the images, preliminary ortho-rectification based on the Mars Orbiter Laser Altimeter (MOLA) DTM is carried out.
- 3. Subsequently, image matching is employed using the normalized cross-correlation coefficient as similarity measure.
- 4. The final sub-step is multi-image least-squares matching for sub-pixel refinement.

The resulting image coordinates of the tie points provide the input for the **bundle adjustment** partitioned into two steps:

(1) First the pointing, described by the angles of exterior orientation, is adjusted for each strip independently. Because the images are not acquired from individual view points but in a continuous motion, the exterior orientation has to be modelled along the spacecraft trajectory as a function of time. The lack of ground control points on Mars is overcome by the use of the MOLA DTM as ground control in a combined bundle adjustment.

(2) In the second adjustment step the whole block is considered. The pointing for each strip is fixed and the relative position between the strips as well as the absolute position of the block with reference to the MOLA DTM is computed. For this step tie points between the different strips have to be available. Thus, tie point matching, as described above, is carried out, using the panchromatic images of two overlapping HRSC strips. As for the selection of single strips, it is important to select only overlaps where the image quality allows for good multi-strip tie points.

The following criteria lead overlaps to be excluded: (1) No tie points where found. (2) The number of tie



Figure 1: Accuracy [m] of HRSC points before (top) and after (bottom) the bundle adjustment

points falls below a threshold (e.g. 10). These points have often a poor accuracy and cause problems in the block adjustment. (3) A first block adjustment of the respective strip pair does not yield acceptable adjustments results. In case all corresponding overlaps of a strip are removed the strip itself is naturally also excluded from the block adjustment.

The processing workflow for large HRSC blocks (with about 90 strips) will be described by taking the example of MC-30 half-tile blocks. The tie point matching strategies and the combined bundle adjustment of HRSC images with the MOLA DTM are discussed based on the results of the MC-11-E half-tile processing.

Results: For the MC-11-E block, the single strip adjustment improves the accuracy of object points on average by a factor of 2.3 ($32,1m \rightarrow 14,1m$). Additionally an improvement factor of 2.1 for the accuracy of multi-strip object points was achieved by the block adjustment ($58,1m \rightarrow 28,0m$). The mean height difference to the MOLA DTM was reduced from 25,4m to 2,7m.

To demonstrate the general validity of this bundle adjustment approach, the results of a range of other MC-30 half-tiles are additionally depicted.

The results of the single strip adjustment and the block adjustment are presented and evaluated in detail. The



Figure 2: Height difference [m] between MOLA-DTM and HRSC points before (top) and after (bottom) the bundle adjustment

intersection error of photogrammetrically determined object points is used for internal accuracy analysis (Fig. 1), whereas differences to the MOLA DTM are used to assess the external accuracy (Fig. 2).

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