GLOBAL MAPPING OF MARS BY SYSTEMATIC DERIVATION OF MARS EXPRESS HRSC HIGH-RESOLUTION DIGITAL ELEVATION MODELS AND ORTHOIMAGES

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Introduction: Since the beginning of its operation in Mars orbit in January 2004, the High Resolution Stereo Camera (HRSC) [1,2] onboard the European Space Agency (ESA) mission Mars Express has returned stereo imagery covering about two thirds of the planet's surface. The gross area coverage of the complete dataset, disregarding multiple coverage of specific areas, is now already on the order of the Earth's land surface. Based on the stereophotogrammetric software developed for HRSC data processing [3], preliminary digital terrain models (DTM) at medium (200m) resolution have been derived at DLR during the course of the mission. Meanwhile, considerable improvements of the orientation data for the instrument have become possible [4,5]. Moreover, refined methods and procedures for the generation of high-resolution DTMs have been developed and evaluated [6], and a systematic comparison of the results of different processing approaches has been carried out under the auspices of the ISPRS Working Group IV/7 on Extraterrestrial Mapping [7]. These experiments and tests on DTM generation have been limited to a small number of exemplary test areas.

DLR has recently taken the responsibility for the systematic generation of HRSC DTM and orthoimages (termed Level-4 products in HRSC project nomenclature) for each HRSC stereo dataset, including the data expected during the remaining part of the extended mission (until fall 2007). Here, we introduce the specifications of the new Level-4 data products. We outline the adopted processing approach, which is centered on the methods for the derivation of high-resolution DTM proposed in [6] (note that the HRSC Level-4 orthoimages, besides the incorporation of improved orientation data, will differ from existing preliminary orthoimages mainly due to the different properties of the underlying DTM). Finally, we present first results of the systematic Level-4 processing.

Instrument and High-Level Photogrammetric Data Products: HRSC is a multi-line pushbroom stereo camera providing up to 5 panchromatic multi-angle observations of the surface during each orbit [1,2]. Simultaneously, multi-spectral imagery is acquired by four CCD lines equipped with spectral filters (near-infrared, red, green, blue). A nominal ground resolution of up to almost 10 m/pixel is being achieved. Beyond stereo capability, HRSC data are unique since a single image sequence covers very large areas (typically on the order of 10^4 km^2) at high image resolution. HRSC is the first photogrammetric stereo sensor system employed in planetary remote sensing. The capability of simultaneous acquisition of stereo imagery avoids changes of imaging conditions which may occur between successive orbital passes and makes pointing maneuvers for obtaining stereo coverage unnecessary.

Specifications of HRSC High-Resolution DTM and Orthoimages (Level-4 Data): The data products of the systematic HRSC Level-4 processing are 8 Bit orthoimages for the Nadir channel and the 4 color channels and 16 Bit DTMs (1 m numeric height resolution), in VICAR format each. The products will also be formatted according to Planetary Data System (PDS) specifications. The map scales of the orthoimages adhere to standard resolutions (12.5, 25, 50… m/pixel), depending on the ground resolution of the respective image. For the specification of the DTM spatial resolution, in addition the quality of orientation and image data is decisive. Usually, a grid spacing of about 2 times the mean stereo resolution (up to 50 m) can be used. Since Level-4 orthoimages are based on the Level-4 DTM, they will be available exclusively for areas covered by the latter. The principal geometric reference for both planimetry and height is a sphere of radius r=3396.0 km as defined by the MOLA team [9]. The IAU ellipsoid [10] or an Areoid can be used optionally. The map projection is Sinusoidal for latitudes between ±85° and Polar-Stereographic for polar areas.

Processing Approach: Photogrammetric processing is based on radiometrically calibrated image data (Level-2) and the data for interior and exterior orientation. Improvements to the nominal orientation data using photogrammetric techniques include a registration to MOLA data by means of height control information derived from the 463m-grid MOLA DTM [11].

Multi image matching is performed using pyramid-based least-squares correlation and is organized as a two-stage process [6]. We introduce an indirect epipolar constraint by reducing search areas to the actually expected residual parallaxes in rectified stereo images. These are produced by orthorectification using DTMs with low resolution compared to the imagery (the MOLA DTM in the first step, and a low-res HRSC DTM in the second step). Note that the utilization of pre-existing DTMs is limited to the initialization of the matching process. The matching criteria applied subsequently are not constrained by any *a priori* height information. Thus, neither MOLA nor the HRSC low-res DTM contribute directly to the derived heights. An essential pre-processing step consists in adaptive (variable bandwidth) Gaussian low pass filtering [6] of the stereo images, which reduces the effects of image compression. 3D Point determination by least-squares forward intersection is followed by blunder elimination (using constraints on the number of stereo observations and thresholding of the intersection error). DTM grid interpolation is done on a pixel basis by distance weighted averaging within a local interpolation radius, which also allows for integrating object points derived at different matching scales.

The overall process involves automatic procedures in combination with individual quality checks based on a set of specific quality measures [6] (see also Table 1) and visual inspection. These may lead to specific modifications of the parameter setting for the particular case. Based on the high-resolution DTM result, a final re-assessment of the quality of co-registration with the MOLA DTM is made, and final adjustments to the exterior orientation data are determined and applied (residual lateral shifts and residual low frequency height undulations at the scale of 10s of kilometers determined by trend surface analysis).

The high-resolution DTM and the adjusted orientation data are applied for orthoimage production. The only additional pre-processing step for the orthoimages consists in a histogram-based linear contrast stretch which does not affect the linear metrics of the radiometric image calibration. Similarly, the Level-3 images (orthorectification based on MOLA) available via PDS and PSA will be successively re-calculated using the new orientation data and product specifications.

First Systematic Results: As prototypes of the new systematic Level-4 products, we derived DTMs (see Table 1 for some DTM quality figures according to the quality measures proposed in [6]) and orthoimages (shown as perspective view in Fig. 1) for four datasets from four different regions on Mars. For all four datasets, it was possible to derive a dense coverage by 3D points showing sub-pixel mean accuracy (the mean 3D error of the orbit 0572 result equals the fifth part of a pixel with respect to mean stereo ground resolution, for example). The reliability of the points is substantiated by high percentages of object points formed by five-fold intersections.

Analyzing height differences with respect to the MOLA DTM also provides useful information on the quality of the resulting HRSC DTM (Tab. 1, Fig. 2). The deviation from MOLA heights needs to be considered carefully, however. Since MOLA is used as external reference in our process, the height differences should be close to zero on average. On the other hand, the area-based approach and the high spatial resolution of HRSC should allow for representing a higher level of topographic detail, which would cause a certain spread of the deviation. The numbers presented in Tab. 1 demonstrate 1) the successful registration of the HRSC DTM to the global MOLA topography (near-zero offsets), 2) the presence of considerable height differences between the two DTM datasets in terms of mean absolute value and standard deviation, 3) the significant reduction of the standard deviation of the differences when data gaps filled by interpolation (in both datasets) are excluded. The last issue suggests that differences associated with data gaps are responsible for a significant but not necessarily predominant fraction of the total deviation between the final DTMs. This broad picture is in agreement with the spatial distribution of the differences visible in the map view (Fig. 2c). The persisting deviation for the "no-gapsfill" case (Fig. 2d) includes precision-related variances from both datasets, but can also be attributed to the difference in resolved detail (the distance between single MOLA shots is 330 m along track, the spot diameter about 170m, while the HRSC DTM have grid spacing of 50-150 m; for more detailed discussion see [6] and [7]). An obvious gain in visible detail is also evident for the shaded relief of the HRSC DTM in Fig. 2b.

Figure 1. Perspective view of the Level-4 red/green/blue DTM and orthoimage for image sequence h2039_0000.

Summary and Outlook: In agreement with previous tests based on larger datasets [6,7], the presented results show that the approach to DTM generation provides 3D accuracy well inside the sub-pixel range, in spite of the compression characteristics of the stereo images. In combination with refined photogrammetric methods for improving orientation data, 3D point accuracy better than 10 m is achieved for some of the highest resolution datasets. Based on the existing results we are confident of envisaging the global mapping of Mars by high-level HRSC photogrammetric data products according to the presented specifications. From preliminary stereo matching tests for an investigation of future landing sites on Mars [8], which involved more than 50 image sequences, we estimated an expected DTM resolution of 50m for ~20% of the respective image sequences and of 75m for more than 60% (based on ground resolution, and the precision and density of 3D points). On the other hand, the quality of a number of datasets is significantly affected by atmospheric conditions, leading sporadically to the complete failure of DTM generation. An important step forward towards possible global coverage has been made recently with the approval of the second Mission extension for Mars Express by ESA.

References: [1] Neukum, G., et al., ESA SP-1240, 17-35, 2004. [2] Jaumann, R., et al., *Planet. Space Science*, 2007, in press. [3] Scholten, F., et al., *PERS* 71(10): 1143-1152, 2005. [4] Spiegel, M., et al., IntArchPhRS (36) 4, 2006. [5] Spiegel, M., Neukum, G., *this meeting*. [6] Gwinner, K., et al., *PERS*, 2007, *subm*. [7] Heipke, C., et al., IntArchPhRS (36) 4: 311-325, 2006,. [8] Gwinner, K., et al., 38th LPSC, #1685, 2007. [9] Smith, D.E., et al., *JGR*, 106(E10): 23689-23722, 2001. [10] Seidelmann, P.K., et al., *Cel. Mech. Dyn. Astron.*, 82(1): 83-111, 2002. [11] NASA, URL: http://pds.jpl.nasa.gov, 2003.

Table 1. Quality figures for the four first High-Resolution DTM derived by systematic HRSC Level-4 Processing.

Image Sequence		**h0572_0000 Tyrrh. Terra**	**h0905_0000 Nanedi Valles**	**h1004_0000 Kasei Valles**	**h2039_0000 Valles Marin.**
DTM Grid Spacing [m]		150	50	75	50
Best Ground Resolution (Nadir / Mean Stereo) [m]		45.1 / 88.6	14.8 / 40.1	16.7 / 41.7	11.6 / 21.7
Intersection Error (Initial / Final) [m][1)]		30.4 / 16.8	42.2 / 9.8	48.5 / 13.4	24.1 / 9.0
Matching Success Rate[2)]		87%	94%	91%	70%
Percentage 3-fold Intersections[2)]		12 %	9 %	21 %	4 %
Percentage 5-fold Intersections[2)]		79%	86%	66%	85%
Height Differences MOLA DTM vs. HRSC DTM [m]	Mean Diff	-0.3	-0.7	-3.2	-2.8
	StdDev of Diff	60.6	42.4	47.3	68.1
	MeanAbsVal Diff	31.0	23.9	27.1	33.8
Height Differences MOLA DTM vs. HRSC DTM excluding data gaps [m] [3)]	Mean Diff	-1.2	-0.2	-3.3	-2.1
	StdDev of Diff	35.5	19.6	27.3	33.4
	MeanAbsVal Diff	24.1	13.8	19.4	21.7

[1)] 3D 1σ-error from intersections, resulting from nominal orientation and improved orientation data, respectively. [2)] Matching image resolution: 4x best ground res. [3)] MOLA463m DTM along measurem. tracks only, and HRSC DTM before gaps-filling by interpolation.

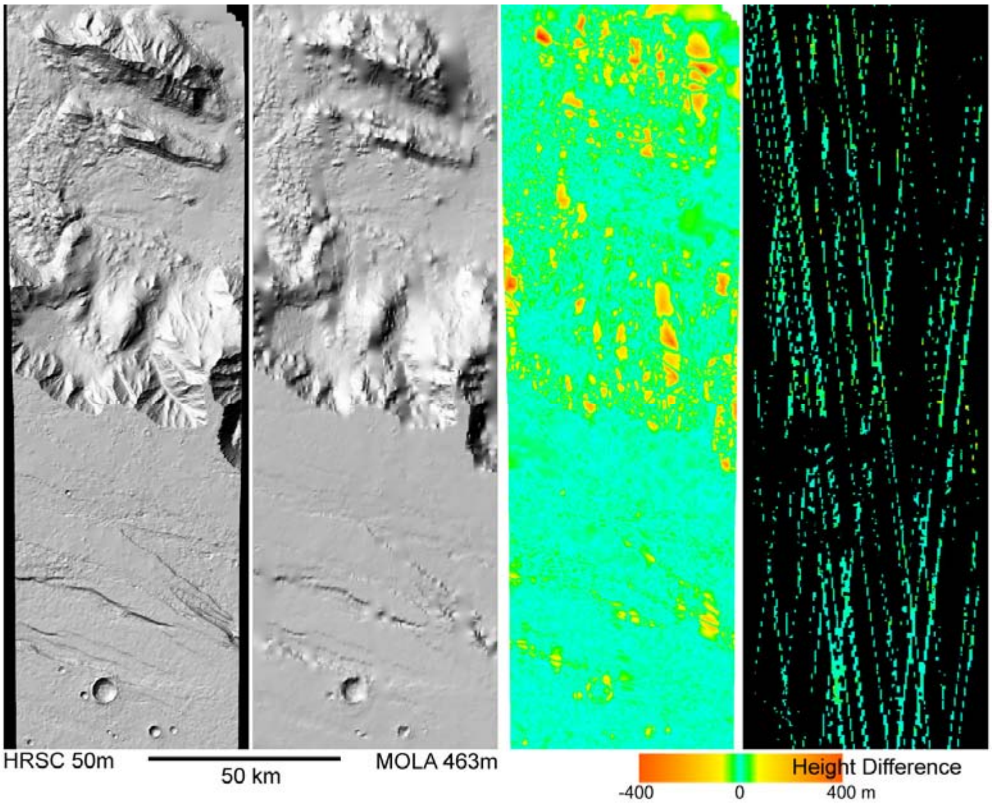

Figure 2. Shaded relief and difference maps of Ophir Labes and Ophir Planum, Valles Marineris. North is downward. From left to right:
a) HRSC 50m DTM, image 2039_0000 b) MOLA 463m DTM c) Height differences between the DTMs d) Height differences between the DTMs, excluding data gaps filled by interpolation.