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Introduction: The *High Resolution Stereo Camera* (HRSC, [1]) is part of the orbiter payload on the *Mars Express* (MEX) mission of the European Space Agency (ESA), orbiting the Red Planet in a highly elliptical orbit since January 2004. For the first time in planetary exploration, a camera system has especially been designed to meet the requirements of photogrammetry and cartography for mapping the complete surface of a planet [2]. For this purpose HRSC operates as a push broom scanning instrument with 9 CCD line detectors mounted in parallel in the focal plane of the camera. Data acquisition is achieved by five panchromatic channels under different observation angles and four colour channels. At periapsis the ground resolution of the nadir channel amounts to 12.5 m, the stereo channels are typically operated at a 2x coarser resolution with the two photometry and the four colour channels at 4x or 8x coarser resolution. The data provided by HRSC are well suited for the automatic generation of *Digital Terrain Models* (DTMs) and other 3D data products. Such products are of vital interest to planetary sciences. As the Mars Express mission has recently been extended the prospects for a complete topographic mapping of Mars by HRSC at very high resolution are very good, indeed.

Image matching is well researched and has been documented in the literature. In general, it is agreed that in “simple” terrain (sufficient grey value variation, not too rough terrain) and with adequate image acquisition geometry (similar flying height, similar direction of optical axes, known relative image rotation if any), very good results can be achieved by totally automated approaches: the matching completeness in these areas reaches 100 %, at a density of various pixels per DTM grid mesh, and the geometric accuracy is well below one pixel. Things start to be much more complicated if more complex situations are faced, such as steep terrain, height discontinuities, occlusions, poor texture, shadows, atmospheric dust, clouds, increased image noise, compression artefacts etc., some of which are commonplace in HRSC images.

Nevertheless, automatic DTM generation from HRSC images by means of image matching has reached a very high level over the years. The systematic processing chain at DLR for producing preliminary DTMs with 200 m resolution [3] runs well and stable. In addition, several groups are able to produce DTMs using different approaches, or have developed alternative modules for parts of the DTM generation process [2]. Also, a few groups have been developing shape-from-shading techniques which have reached pre-operational efficiency.

It is against this background that the desire was expressed to compare the individual approaches for deriving DTMs from HRSC images in order to assess their advantages and disadvantages. Based on carefully chosen test sites the test participants have produced DTMs which have been subsequently analysed in a quantitative and a qualitative manner. This paper reports on the results obtained in this test, more details can be found in [4].

Test goals and organisation: Key goals of the test were the reconstruction of fine details and the geometric accuracy of the DTMs. Fine detail is studied using a variety of qualitative assessments in small but representative areas, while geometric accuracy is analysed with respect to the MOLA DTM (Mars Orbiter Laser Altimeter, [5] [6). This DTM is the most consistent Mars DTM available to date. Note that the geometric analysis suffers from the lack of a reference data set with superior accuracy, mainly because the MOLA DTM does not have an adequate planimetric resolution. The quantitative results presented in this paper therefore relate to the differences between the HRSC DTM and MOLA DTM, and incorporate the inaccuracies inherent in both sources. In addition, many groups used MOLA information already as input for their procedures[1], making an independent check of the results somewhat questionable. Nevertheless, such computations are useful, because differences in the results from participant to participant can be linked to the individually generated HRSC DTMs. All quality parameters were also related to operational aspects such as the computing effort of the applied method, and thus its

[1] MOLA is used as control information in the bundle adjustment, as a surface for pre-rectification prior to matching, for fitting results of individual strip DTMs and for filling holes resulting from matching blunders. The degree to which the participants made use of MOLA varies (see section 4).

applicability to generating DTMs of large areas (multiple orbits, potentially the whole HRSC data set).
The test was organised by the Photogrammetry and Cartography WG within the HRSC Co-I team under the auspices of the ISPRS WG IV/7 on *Extraterrestrial Mapping.* IPI, University of Hannover, and DLR Berlin-Adlershof acted as pilot centres for the test. Two data sets were chosen for the test: the HRSC images h1235_0001, and a block of three adjacent images, numbered h0894_0000, h0905_0000, and h0927_0000. In addition to the processing of complete orbit images, sub-areas were defined for contributions of limited areas. The sub-area in image 1235 covers western Candor Chasma at approximately -8° to -4°N and 282° to 284°E, and includes the spectrally distinctive Ceti Mensa. This sub-area exhibits many steep slopes and a number of horizontal plateaus with very little texture. The second sub-area covers Nanedi Vallis at approximately 2.5° to 7.5°N and 310° to 314°E. In this area many craters of different size are visible, the Nanedi orbits also provide a test of capabilities for producing seamless DTMs from blocks of images. For the test sites image orientations refined by bundle adjustment were also delivered. A total of eight groups have derived DTMs. The pilot centres then analysed the data produced. To our knowledge this is the first multi-site test for DTM generation from planetary imagery.

Results: Overall, he test was successful and has demonstrated that a number of methods exist, which are able to generate high quality DTMS from HRSC imagery. Nevertheless, noticeable differences in the participants' results were found. Some approaches yield superior results, not surprisingly these are the approaches which were developed with planetary imagery in mind, and those which have been extensively applied to planetary and in particular to HRSC image data in the past. While DLR-Scholten and DLR-Hirschmüller turned out to be the most operational methods in terms of processing time (per orbit only few hours are needed), the approaches of DLR-Gwinner and DLR-Gwinner/ipf yielded the best overall results in terms of accuracy and fine detail, still providing operational production times with only a few days processing per orbit. Thesolutiojns based on shape-from-shading (USGS and DLR-Scholten/ UniBW) resulted in remarkable improvement in detail. Furthermore, the test confirms previous findings that the DTMs generated from HRSC data, at least at lower latitudes, are clearly superior to the MOLA MEGDR in terms of resolution and visible fine detail. Very detailed DTMs can be generated from the HRSC images; at least in some areas it appears to be feasible to use a DTM grid size of two to three times the resolution of the nadir image.
The geometric accuracy of the derived DTMs varies with terrain characteristics (undulation, texture, etc.). As measured against MOLA tracks a standard deviation of approx. 20 m in height (which corresponds to a ground resolution of one pixel) could be reached for the relatively flat Nanedi test site in the best case. For the more complex Candor Chasma image with a number of steep slopes, less image contrast and more radiometric noise, a standard deviation of two pixels was obtained in the best case. These results correspond to the values which are reached in aerial photogrammetry using image matching and can thus be classified as excellent taking into account the generally low texture of planetary images. While manual editing is known to be able to improve the results particularly with respect to blunder elimination, the test did not focus on evaluating this aspect. Given the sheer amount of data in planetary missions, manual mapping is very costly, and automation is thus the only realistic way to produce results with a reasonable amount of resources. Nevertheless, some manual elimination of blunders may be necessary to achieve highest standards for DTM accuracy, but cost-effectiveness requires that this step be minimized by optimizing the performance of the automated matching.

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