Mars Express HRSC Data Processing – Methods and Operational Aspects

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Abstract
Automated procedures for ground processing of Mars Express HRSC data have been developed and are applied systematically immediately after download in order to provide calibrated data sets as well as photogrammetric image and 3D data products within a short time frame. Multi-spectral orthoimages in scales of 10 m to 50 m/pixel and digital terrain models of 200 m raster width are generated within days even for large orbits covering areas of several hundred thousand square kilometers. An even higher image resolution of up to 2.3 m/pixel provided by HRSC's Super Resolution Channel (SRC) extends the potential of the HRSC camera experiment.

Introduction
The High Resolution Stereo Camera (HRSC) experiment on the European Mars Express Mission (MEX) has been specifically designed for 3D mapping purposes (Neukum *et al.*, 2004). It offers a huge potential for the generation of high-resolution, multi-spectral, and three-dimensional data products. After the launch in June 2003 and transit to Mars, MEX entered Mars orbit on 25 December 2003. As a part of the MEX commissioning phase, HRSC, operated by the German Aerospace Center (DLR), Berlin, began its campaign on 09 January 2004. The commissioning phase ended in early June 2004 when MEX reached its final operational orbit. The nominal mission will last one and might be extended to two Martian years (two representing four Earth years). MEX HRSC aims at mapping a large portion of the surface of Mars with high spatial resolution, with multiple stereo and in five spectral bands. In this paper, we give an overview of the associated HRSC ground data system and its application for the generation of photogrammetric data products on a standardized routine base. A brief quality estimation of the resulting data products and an outlook on projected extensions of the standard processing line complete the following description.

MEX HRSC/SRC Camera and Data Properties
The full exploitation of the HRSC potential for systematic and stereo-photogrammetric processing requires methods which take into account the specific geometric characteristics of the applied multi-line pushbroom sensor type and the imaging conditions during the mission.

Camera Parameters
The HRSC camera (Neukum *et al.*, 2004) is a multi-line pushbroom scanner comprising nine CCD-lines in the focal plane of a 175 mm optics for high-resolution, multi-stereo, and multi-spectral data acquisition. The Super Resolution Channel (SRC), equipped with an additional 975 mm telescope, extends the HRSC imaging capabilities. An overview of the technical parameters of HRSC and SRC is given in Figure 1.

Data Formats
While SRC provides one panchromatic band of conventional frame image data of 1k × 1k pixels, HRSC generates image strips of 5,184 data pixel per line and up to several hundred thousand image lines. The HRSC/SRC image and housekeeping data are stored in the VICAR (Video Image Communication and Retrieval; NASA, 1995) format, which is also used as processing platform. Data for orbit, pointing, and clock timing are generated in NASA's NAIF/SPICE format and software toolkit which is MEX HRSC's basic environment for other ancillary data, e.g., body ephemeris and planetary constants (Roatsch *et al.*, 2001).

Geometric/Radiometric Data Properties and Imaging Conditions
The HRSC line sensors were radiometrically and geometrically calibrated based on extensive laboratory measurements in 1995 and 1996. During a re-evaluation in 2001, it could be verified that the calibration data are still valid. The SRC was radiometrically calibrated in 2002 shortly before delivery to ESA. Unfortunately, there was no time for a geometric calibration. The calibration software and datasets were verified and improved during cruise phase.

The operational orbit of MEX is defined by 250 km pericenter altitude and 10,100 km altitude at the apoapsis. The HRSC ground sampling distance (GSD) of each pixel varies within an image strip depending on the actual altitude. Thus, a high GSD of up to 10 m/pixel at 250 km pericenter altitude is obtained in combination with large coverage of up to several hundred thousand square kilometers per image strip. All nine channels of HRSC acquire image data in parallel and with a radiometric resolution of 8-bits/pixel. Switch-on and off points of each sensor are planned and commanded so that data of each sensor fully covers the intended target area. The exposure time of each image line is adapted successively within an orbit sequence, depending on the actual

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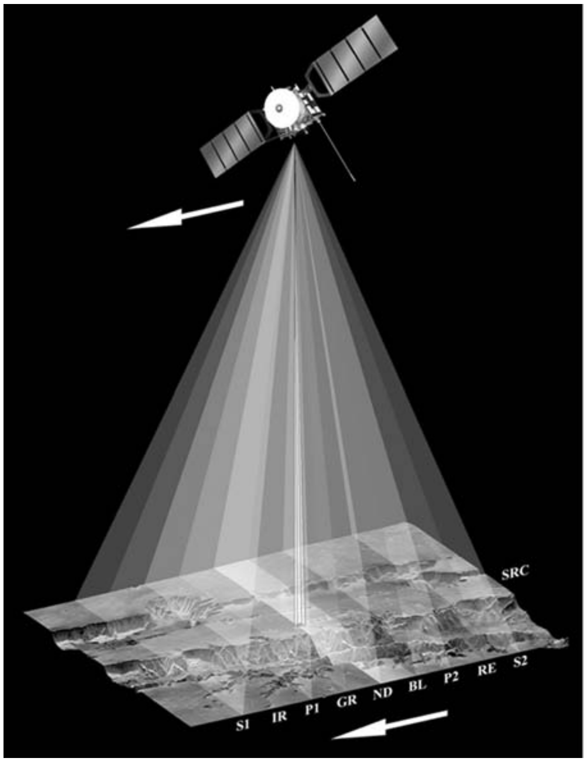


	HRSC	SRC
Image principle	multi-line pushbroom	frame
Image size	5,184 pixels/line (9 CCD lines)	1k x 1k
Focal length	175 mm	975 mm
IFOV	8.2 arcsec	1.9 arcsec
Stereo channels	5 0 deg +- 12.8 deg +- 18.9 deg	-
Spectral bands	5 panchromatic near-infrared red, green, blue	1 panchr.
Radiometric resolution	12 bit	12 bit
On-board compression	JPEG	-

Figure 1. Imaging principle and technical parameters of HRSC and SRC.

spacecraft velocity in order to yield approximately same across-track and along-track ground sampling distance, gain settings depend on the solar elevation and the mean expected surface albedo. Both on-board data compression and macro-pixel binning are used to tailor the acquired data volume to the available mass memory and data rates. The general mode of SRC operations provides single full-resolution images in the center of the HRSC swath, which can be timed to overlap in flight direction. The nominal SRC image resolution is 2.3 m/pixel at 250 km pericenter altitude, its radiometric resolution is 14-bit/pixel.

The alignment of the SRC with respect to the HRSC line sensors and of the line sensors with respect to the spacecraft was not measured before launch. Therefore, this alignment was estimated within two star calibration sequences, one during cruise and the second shortly after arrival at Mars.

Data Processing Overview

DLR's operational HRSC/SRC ground data system consists of two main complexes, the systematic processing of the raw data and the photogrammetric processing for the derivation of orthoimage and 3D products.

Automated Systematic Processing of Raw Data

This fully automated procedure is applied immediately after the download of the data and consists of the conversion of the original data stream transmitted to ground to de-compressed data (Level-1 data), the radiometric correction of the image data based on calibration information (Level-2 data), and the map projection of all data using standard map parameters (Level-3 data). This last step includes a differential image rectification, where the different imaging principles of HRSC and SRC are taken into account. A low-resolution topography model (5 km/pixel digital terrain model derived from MOLA data) and original SPICE orbit and pointing data are used within this ortho-rectification process. Level-2 and Level-3 data are distributed to the PI and the entire HRSC Co-Investigator team.

Automated Standard Photogrammetric Processing for the Derivation of Image and 3D Products

Operational standard procedures have been developed at DLR in order to derive HRSC image and 3D products automatically within a short time frame for each image strip. These products (Level-4) are HRSC digital terrain models (DTM) on 200 m grids and orthoimages of all sensors in resolutions, depending on their original GSD, of 12.5, 25.0 or 50.0 m/pixel based on the corresponding HRSC DTM. Standard image and 3D products are generated with the goal of fast availability for first scientific investigations.

Figure 2 gives an overview of the MEX HRSC data processing and analysis tasks related to the generation of HRSC/SRC image and 3D data products. Systematic data processing and standardized photogrammetric data processing within the MEX HRSC ground data system are performed on Linux-PC clients at DLR. Shell scripts are used to define the procedures and parameters. The procedures are started manually when new data have been downloaded. Scripts may also start automatically based on pre-defined logging of previous processing steps (e.g., standard Level-4 processing is initialized by logging of Level-2 completion).

The derivation of detailed higher level data products such as DTM on 50 m grids, needed for more intensive scientific data analysis, is not in the focus of this paper. Although built upon similar procedures, the main difference in terms of operational aspects lies in the higher need for adaptive processing techniques and longer processing times.

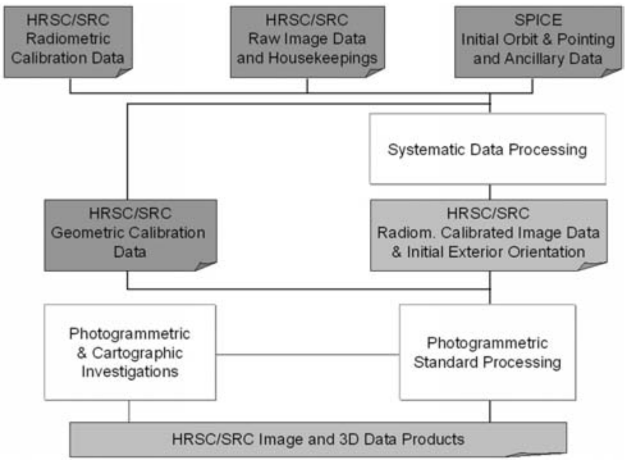


Figure 2. Overview of MEX HRSC data processing and analysis tasks related to the generation of HRSC/SRC image and 3D data products.

Complementary investigations of the MEX HRSC Photogrammetry and Cartography Working Group address the extension and improvement of photogrammetric and cartographic output of the experiment (Albertz *et al.*, 2005), and thus complete the photogrammetric data analysis activities. In particular, the derivation and application of adjusted exterior orientation (orbit and pointing) is aimed at improving the interior quality of the data products and the absolute accuracy for integration of HRSC products into existing topographic reference data sets (e.g., Mars topography described by MOLA).

Data Calibration and Systematic Processing

The data from all Mars Express instruments are received at ground stations of ESA and NASA. The European Space Operations Centre (ESOC) collects these data, separates the data from individual instruments, and performs a first quality check.

ESOC also provides predicted and reconstructed orbit and attitude data. These are delivered in SPICE kernels. The HRSC data together with additional housekeeping data and the SPICE kernels are transferred to the HRSC data processing center at DLR.

The first step of the following systematic data processing (see Figure 3) is the telemetry processing which consists of three components:

- separation of the different sensor data,
- conversion of the housekeeping data and the combination with the respective image data, and
- decompression of the data.

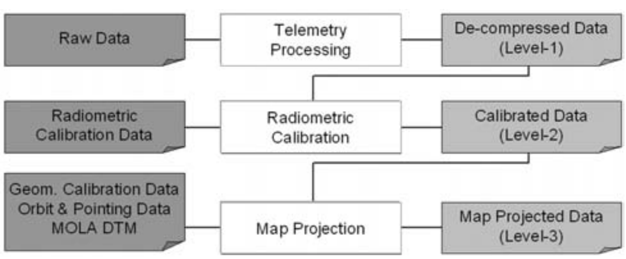


Figure 3. MEX HRSC systematic data processing.

The next processing step is the radiometric calibration using the derived data described above. The results of this step are stored as 16-bit short integer data since normalizing the original image sequences, which comprise subsets acquired with different exposure times, to a common radiometric standard can lead to a dynamic range of more than 8-bit. The last step is a map projection of the data where a global low resolution MOLA DTM is used as reference topography model (we use the term "MOLA DTM" in this paper for the gridded representation of the Mars topography as provided by the MOLA planetary radii model (Smith *et al.*, 2003). It is coded as terrain heights geometrically defined above the MOLA reference sphere with a radius of 3,396.0 km). Figure 4

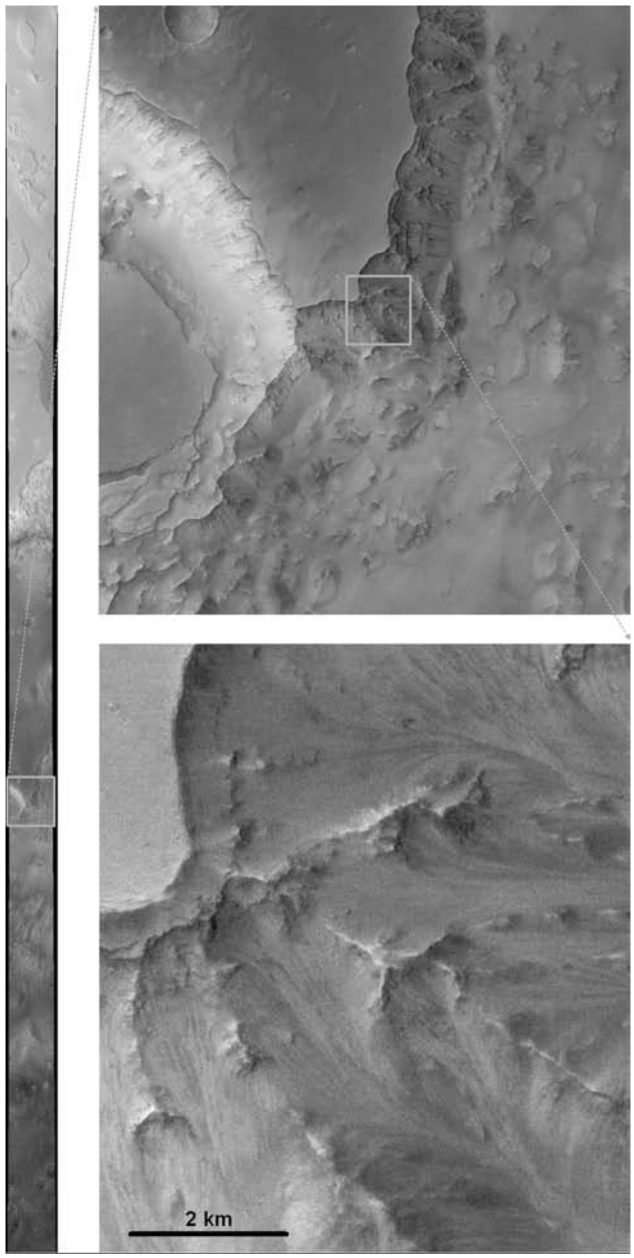


Figure 4. Panchromatic Level-3 data of MEX Orbit 0018, acquired on 14 January 2004, ortho-rectified to 12.5 m/pixel (North/South extension 1,660 km, 323° East, subset at 5.4° South).

gives an overview of an exemplary map projected panchromatic data set (Sinusoidal Projection) of a complete orbit and additional subsets up to full resolution.

Both, radiometrically-corrected data and map-projected images are distributed to the MEX HRSC COI team. Furthermore, the radiometrically corrected data will also be converted to Planetary Data System (PDS) format and will be distributed by ESA-PSA (Planetary Science Archive) and NASA-PDS to the international scientific community.

The information of all processed image data is stored in a database at DLR. The CoI team can access this database through a web-based catalogue developed and maintained by the Technical University of Vienna. This interface, the Topographic Mars Information System (TMIS) (Dorninger, 2004), allows standard queries of the data using topographic names, orbit number, and sensor name.

Photogrammetric Data Processing

The multi-stereo and multi-spectral capabilities of HRSC enable procedures for high-resolution, photogrammetric stereo analysis, as well as orthoimage generation to derive valuable base products for a variety of geo-scientific investigations, as demonstrated also in first airborne applications of the MEX qualification model in Earth science (Gwinner *et al.*, 2000). The methods applied within HRSC data processing for the MEX mission are similar to those developed and applied within different airborne DLR projects during the past years, where, in addition to the qualification model of the MEX mission, different derivatives of HRSC have been flown in altitudes of 2,000 m to 10,000 m (Neukum, 1999; Wewel *et al.*, 2000; Scholten *et al.*, 2002). The data have been processed to orthoimage mosaics of 10 to 50 cm/pixel and to 50 to 100 cm digital surface model grids.

DLR's photogrammetric processing software system (Figure 5) represents the core of the entire photogrammetric and cartographic activities within the MEX HRSC CoI-team and makes it possible to provide photogrammetric data products to the team. While more elaborate high level data products are generated on the basis of specific co-operative CoI investigations, the operational and standardized generation of products, which is under the focus of this paper, aims mainly at:

- allowing for a quick availability of higher level data products (orthoimages and 3D surface description available within days),
- warranting full exploitation of the entire HRSC potential (multi-stereo capability for reliable 3D modeling, as well as precise high-resolution and multi-spectral orthoimage generation), and
- achieving a high degree of automation (without manual interaction in order to ensure a quick availability of products).

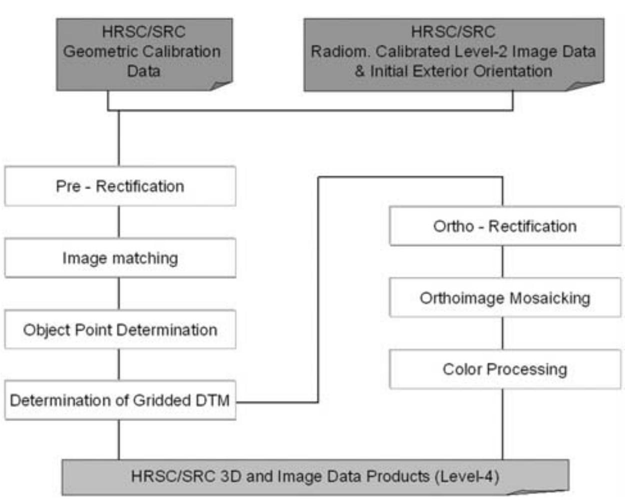


Figure 5. Overview of the DLR photogrammetric processing software system.

In consideration of the previously described camera characteristics, data properties, and imaging conditions, the developed methods have been assembled to a straightforward processing strategy which has been applied systematically since the start of HRSC data acquisition onboard Mars Express.

DTM Generation

One of the fundamental qualities of HRSC, besides its high-resolution and multi-spectral capabilities, is its multi-stereo capability. The derivation of 3D topography represented in a DTM consists of the determination of conjugate points on a dense regular search grid for the entire orbit within multiple stereo channels (image point determination), the combined forward ray intersection based on image coordinates and interior and exterior orientation (object point determination), and the generation of a DTM raster grid based on the object point coordinates.

Image Point Determination

Image point determination consists of three steps: the generation of quasi-epipolar geometry by pre-rectification, an area based multi-image matching, and the back-transformation of matched image coordinates to original Level-2 image geometry.

- **Pre-Rectification**: Based on given orbit and pointing information the five stereo-channels are pre-rectified to a constant pixel scale in a common map projection. Thus, all stereo data sets of an orbit are fitted to a common geometry. To reduce the search areas for the matching algorithm, the MOLA DTM is introduced as *a priori* topography information. Consequently, the along-track x-parallaxes between the stereo channels are removed to first order. Remaining parallaxes reflect, besides a possible misfit of the used and the true exterior orientation, the difference between the assumed and the true topography. Across orbit y-parallaxes are small since the pre-rectified images define a quasi-epipolar geometry. For further processing these x- and y-parallaxes appear as line and sample parallaxes, since the pre-rectified data are oriented to the North which corresponds to the orbit inclination of 87 degrees. During the pre-rectification process, the Level-2 image coordinates of each pre-rectified pixel are stored. This is necessary since orientation data can only be adapted to Level-2 coordinates within the following object space forward ray intersection of multiple-stereo rays. In order to minimize the memory requirements for storing this "history" of each pixel (at least 2 times 4 Byte for line and sample values), a run-length coding utilizing specific regular patterns of these data has been developed. This compression yields a data reduction of about 90 percent and preserves an image coordinate accuracy of 0.1 pixel.
- **Multi-image Matching**: Based on pre-rectified image data, a multi-image matching technique is applied to derive conjugate points in each of the five stereo channels. The algorithm makes use of area-based correlation in image pyramids to derive approximate values for the image coordinates, which are refined with sub-pixel accuracy by least-squares matching (Wewel, 1996). Due to the pre-rectification and the orientation of the image file along the orbit path, parallaxes caused by terrain height mainly appear in flight direction

(*x*/line-parallaxes), while *y*/sample-parallaxes are small (only few pixels). The standard correlation is done for each of the four stereo channels with the nadir channel as reference, but can be extended to all possible combinations and reference channels. A pyramidal approach using stepwise reduction of the correlation patch size yields moderate computation times even with large *x*-parallaxes.

- **Back-transformation to Level-2 Coordinates**: After the multi-image matching process, the derived image coordinates of all stereo channels are transformed back to Level-2 geometry using the compressed Level-2 history files generated during the pre-rectification. The accuracy of this back-transformation is better than one tenth of a pixel.

Object Point Determination

Each determined line/sample pair of image coordinates for all stereo channels can now be combined with the interior and exterior orientation data. Based on the geometric calibration, each sample coordinate defines the camera interior position on the specific stereo CCD-line, while the exterior orientation for the line coordinate can be interpolated within the orientation made available for each image line by the systematic processing. The lines of sight, defined by each stereo channel coordinate pair, are used for forward ray intersection. Least-squares adjustment is applied for this over-determined problem. The result is an object point and its relative accuracy defined in body-fixed Martian cartesian coordinates. The redundancy given by HRSC's multi-stereo capability allows us to accept only those object points, which are defined by a chosen number of stereo observations. Thus, the influence of occasional gross matching errors, which cannot be avoided by simple two-image matching, is minimized. Nevertheless, also two-image matching results may be used in case of insufficient multi-image matching results (e.g., due to effects caused by compression artefacts or lack of image texture).

DTM Raster Generation

MEX HRSC raster DTMs are generated as map referenced raster grids in a VICAR 16-bit signed short integer image format. For the generation of a grid in the map projection, the object points are first transformed from Mars body-fixed cartesian coordinates to geographic latitude/longitude/height values based on a three-dimensional reference system (we use the Mars IAU ellipsoid as the MEX HRSC standard reference system and, for comparison with MOLA products, the Mars sphere as defined by the MOLA science team). The geographic latitude/longitude coordinates are transformed to standard map projections (Sinusoidal projection for equatorial regions up to 85° Northern and Southern latitude, Lambert Azimuthal for polar regions). The final DTM height values are derived at the DTM pixel level. Object points located within a DTM pixel are averaged and can optionally be combined by different filtering techniques with those within a chosen neighborhood. For regions which lack any object point information a final gap-filling algorithm using DTM pyramids with reduced resolution can be applied in order to derive a raster DTM without gaps. If requested, the geometrically defined ellipsoidal heights may finally be converted to heights above a physical reference surface, e.g., the Mars IAU areoid. Figure 6 shows an exemplary gray value coded HRSC DTM for the same orbit as presented in Figure 4.

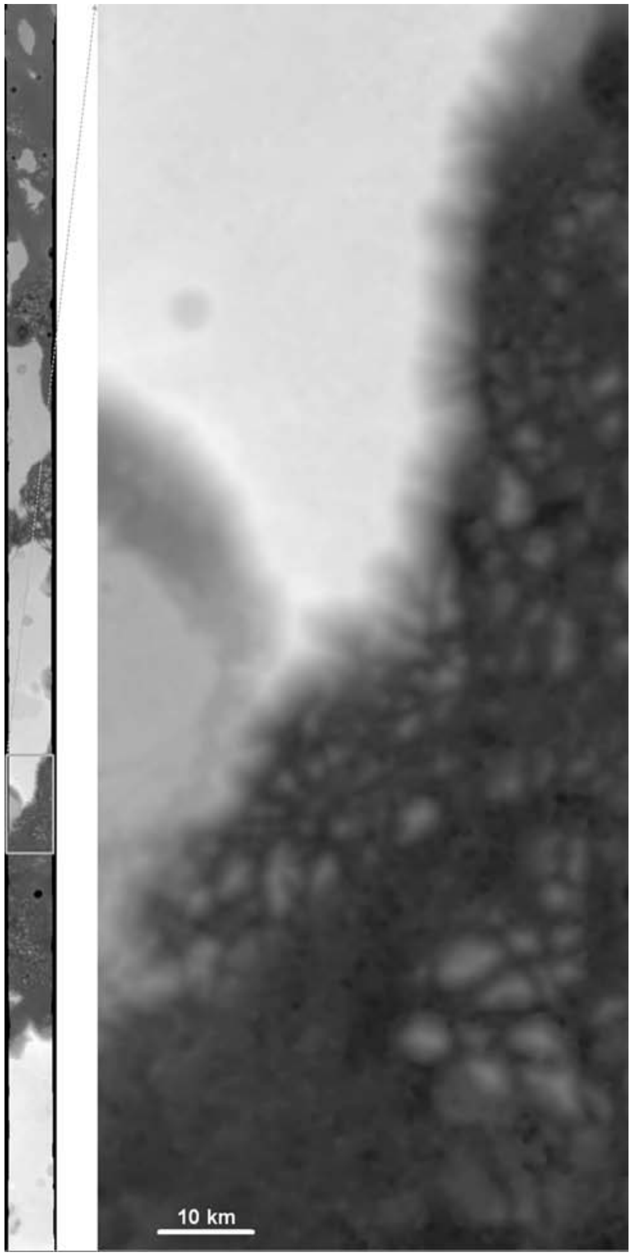
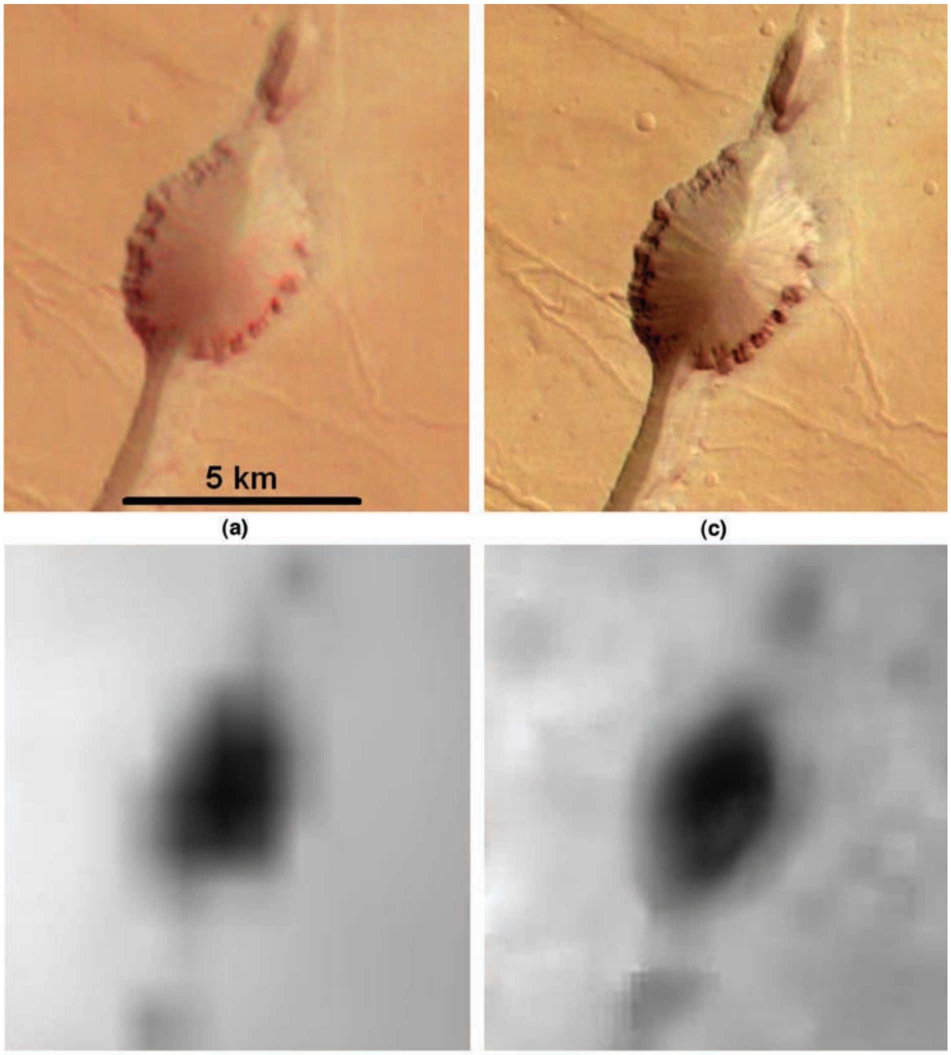


Figure 6. Gray value coded 200 m HRSC raster DTM with a height range of approx. 5,500 m, MEX orbit 0018, acquired on 14 January 2004 (North/South extension 1,660 km at 323° East).

Orthoimage Generation

Based on the knowledge of the topography represented by the HRSC DTM, the data of each HRSC channel can now be ortho-rectified more precisely than within the standard Level-3 generation based on the topography described by MOLA (Plate 1) which is often incomplete and therefore interpolated because of large MOLA track separations in equatorial regions (Smith *et al.*, 2003). Considering the large size of the input and output data sets (the HRSC orthoimage size may be up to 10 GB) and for reduction of computer memory requirements, the rectification is internally divided into several parts. The ortho-rectification consists of a ray-tracing process of regular pixel positions of the input Level-2 pixel matrix with the HRSC DTM using interior camera calibration and exterior orientation data related to the respective pixel (Scholten, 1996). For each grid point, a 3D intersection point with the DTM is derived and transformed to the map projection of the output orthoimage (same standard projections as for the DTM). For each pixel within a mesh of these



(a) (c)

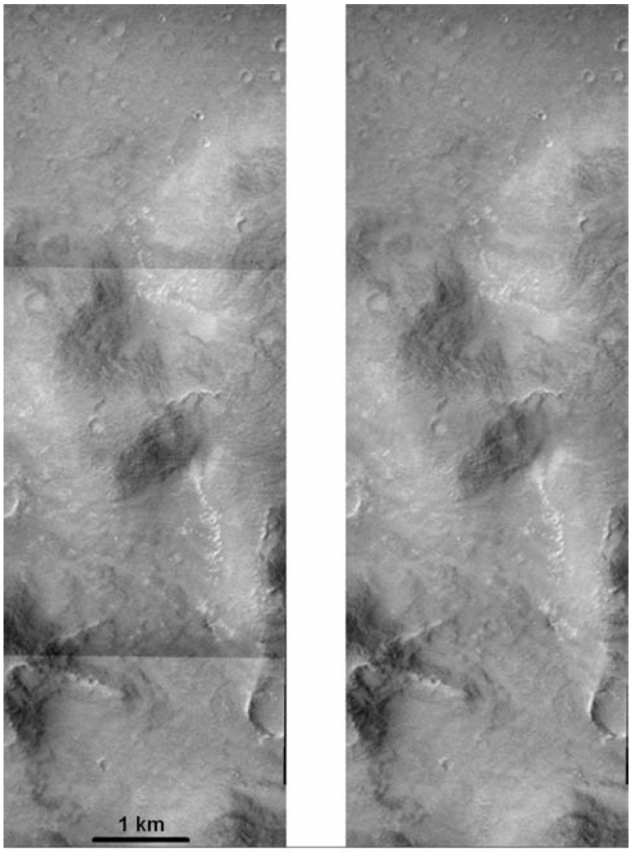
(b) (d)

Plate 1. Comparison of a Level-3 red-green-blue composite (a) based on MOLA DTM (b) with a pan-sharpened Level-4 representation of the same imagery (c) based on the HRSC 200 m DTM (d) with a height range of approx. 1,000 m. Note the presence of color seams in the Level-3 image resulting from inappropriate representation of topography with respect to the resolution of the orthoimage. By contrast, the Level-4 image shows good co-registration which allows us to apply pan-sharpening. (North of Albor Tholus, 23° North, 150° East, subset of MEX Orbit 0032, acquired on 19 January 2004).

transformed grid points, an indirect resampling based on different selectable interpolation methods is performed within the Level-2 input matrix in order to derive the final orthoimage grey value. Finally, ortho-rectified HRSC color and panchromatic channels, if rectified to the same map projection and pixel scale, fit to each other with the accuracy provided by the DTM and the applied orientation data and can be superimposed as co-registered multi-spectral/multi-phase data sets.

Orthoimage Mosaicing

Ortho-rectified HRSC data sets of single MEX orbits need to be combined for mapping of target areas spread over different orbits. For this purpose, a radiometric mosaicing tool has been developed. It combines all input orthoimages by simply copying them to one common image mosaic and provides different optional features for brightness adjustment (using image information in overlapping areas) and to produce seamless transition from image to image by weighted averaging of overlapping image parts. No geometrical adjustment is applied, the geometric relationship between the images to be mosaiced is considered to be fixed and is defined by each image's label information comprising nominal map projection parameters, scale, and the offset of its upper left pixel with respect to the projection center. Figure 7 shows an example of a mosaic of individual SRC images with and without brightness adjustment. Figure 8 provides an example of a mosaic with radiometric adjustment derived from adjacent HRSC images.



(a) (b)

Figure 7. Mosaicing of SRC images without (a) and with (b) a seamless transition from image to image by weighted averaging of overlapping pixel information. (Gusev Crater, 15° South, 175.5° East, subset of MEX orbit 0024, acquired on 16 January 2004).

Operational Standard Processing of Level-4 Products

The methods described before are available for application in a variety of different modes. Since the primary aspect of HRSC standard photogrammetric processing is quick availability, dedicated procedures comprising the entire processing chain have been set up to generate first Level-4 products (DTM and orthoimages) automatically within hours after Level-2 availability. Although focusing on a fast generation of products, these procedures also take advantage of the fundamental capabilities of the HRSC imaging principle. Standard Level-4 product generation is started immediately after completion of systematical Level-2 generation and is applied to all HRSC mapping data (no standard Level-4 generation is performed for limb scans, star calibrations, observations in HRSC modes without stereo data acquisition, and of observations of the Martian satellites Phobos and Deimos). Plate 2, a mosaic of panchromatic orthoimages, overlayed on a global MOLA relief map, gives an overview of all orbits processed until end of March 2005. The data cover about 46,000,000 km^2 of the surface of Mars (65 percent of these data comprise image resolutions for the nadir channel of 10 m to 30 m/pixel). Since the MEX orbital and pointing information valid for these data are not improved by any adjustment, the geometry of the entire standard processing relies on the quality of the initial orientation available at that time (nominal or reconstructed orbit data).

Image matching is applied to all stereo channels with respect to the nadir channel as reference within standard Level-4 generation. Other stereo combinations, in particular those comprising only two channels, are not used since their potential lack of reliability of the initial exterior orientation is likely to decrease the product quality. Data used within the matching process are pre-rectified to a 100 m/pixel scale. Each second pixel of the pre-rectified nadir channel is used as reference for correlation with the four stereo channels.

Object points are calculated by forward ray intersection only for those points, where conjugate line/sample coordinates could be determined in at least three stereo channels (including the nadir) and for which their relative forward

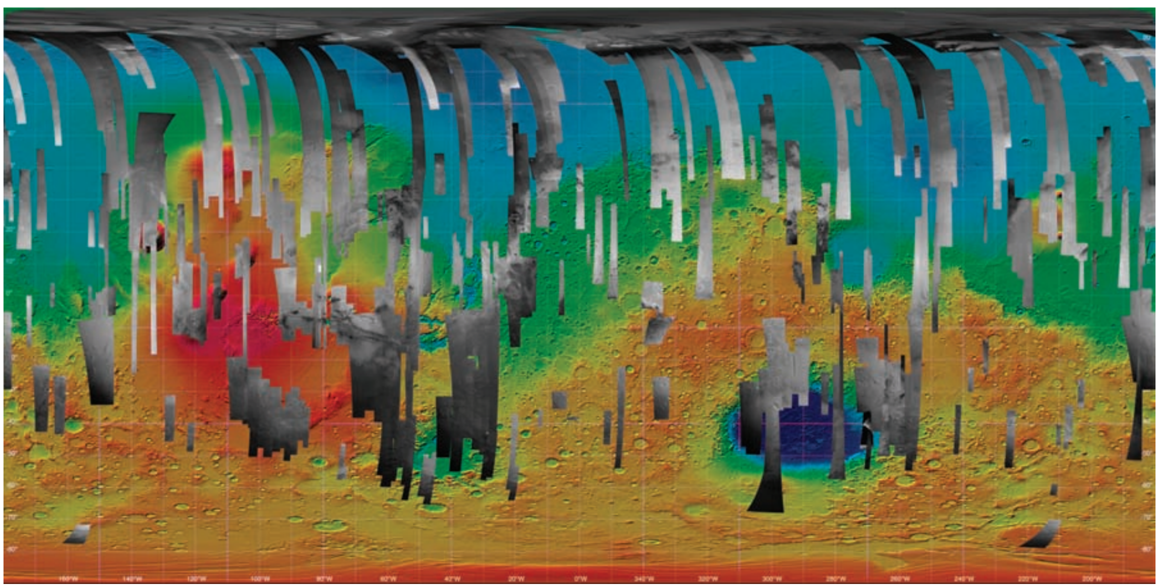


Plate 2. Mosaic of panchromatic orthoimages, displayed on a global MOLA relief map. The image tracks represent all MEX HRSC mapping orbits until MEX Orbit 1550 (March 2005).

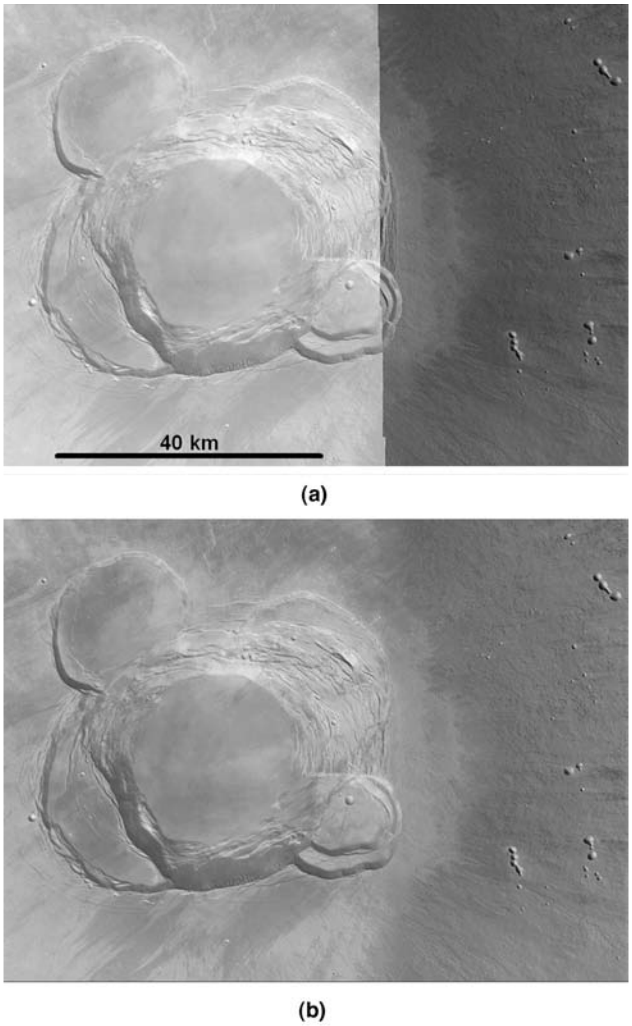


Figure 8. Orthoimage mosaic derived from panchromatic nadir images of subsets of MEX orbits 0016 and 0068. (a) without adjustment, (b) after radiometric adjustment. (summit caldera of Ascraeus Mons volcano, 11° North, 255.5° East, acquired on 13 and 31 January 2004).

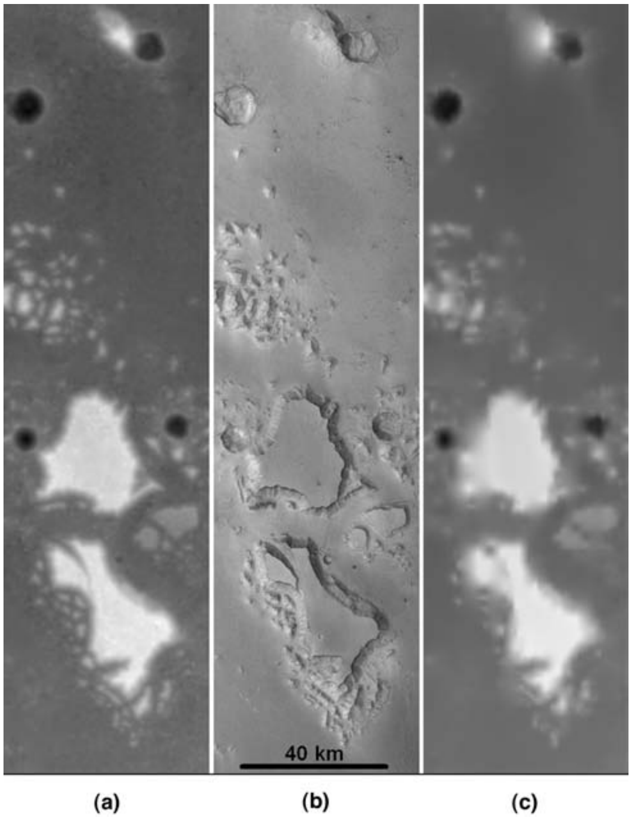


Figure 9. Example of a 200 m raster DTM (a) with a height range of approx. 3,000 m and a Level-4 orthoimage of the panchromatic nadir channel, ortho-rectified to 12.5 m/pixel (b). For comparison, also the interpolated MOLA DTM is shown (c). (Part of the Chaotic Terrains, 10° North, 323° East, subset of MEX Orbit 0018, acquired on 14 January 2004).

intersection error is better than the overall 2 sigma RMS. Then, with respect to the grid of candidate match points, a 200 m DTM grid is interpolated from the object points.

Orthoimage generation is done in standard map scales of 12.5, 25, or 50 m/pixel. The scale of the ortho-rectification is automatically selected for each orbit and each sensor such, that the best nominal ground sampling distance within an orbit is preserved. Special map projection parameters for each orbit, e.g., the reference meridian (center longitude), are selected depending on the image location in order to minimize orthoimage map distortions.

Standard photogrammetric data processing is applied to each HRSC mapping orbit. The total output comprises a 200 m raster DTM and orthoimages of up to 12.5 m/pixel scale for the color channels near-infrared, red, green, and blue, as well as for the panchromatic nadir channel. This takes only hours or few days for the largest image data sets of more than 200,000 lines (covering more than 400,000 square kilometers). Figure 9 shows an example of a 200 m raster DTM and a Level-4 orthoimage of the panchromatic nadir channel.

Quality Assessment of 3D Products Derived by Standard Processing

Detailed quantitative statements about the data quality, the accuracy of the entire data processing line, and the derived products deserve intensive studies and statistical analyses, since the geometrical conditions of each orbit are different. Especially within the commissioning phase, orbit maneuvers do not allow for a consistent quality of orientation data. In addition, the impact of atmospheric conditions, variable local texture, and varying illumination conditions are difficult to include in an overall quality assessment. Nevertheless, first general statements can be made based on the present Level-4 standard processing statistics.

Density of Object Points

As a first measure for 3D surface reconstruction quality, the average object point density, resulting from the procedure for the standardized generation of DTM products described above, is estimated:

- successful image matching versus attempted image matching: => up to 90 percent in textured regions, <10 percent in extreme low-textured flat regions,

- matching results with at least three stereo observations versus all successful matching results:
  => approximately two-thirds, and
- points with relative forward intersection error better than 2 sigma RMS:
  => 95 percent.

The average object point density derived from a 200 m grid (25 points/km^2) matching within the standard Level-4 processing is estimated as approximately 15 to 20 points/km^2 for well textured areas and as 0 to 2 points/km^2 for low-textured regions.

Mean Interior 3D Accuracy

For the first 136 orbits with HRSC data acquisition standard Level-4 processing generated several hundred millions of object points (derived by image matching in pre-rectified 100 m/pixel imagery and based on initial orientation data). The mean relative inter-stereo forward intersection error (1 sigma RMS) of these points shows:

- 87 percent orbits better than 200 m 3D accuracy,
- 60 percent orbits better than 100 m 3D accuracy, and
- 12 percent orbits better than 50 m 3D accuracy.

First results of experiments aimed at improving 3D accuracy, e.g., based on exterior orientation improved by bundle block adjustment, show that a relative point accuracy of up to 10 m to 20 m can be achieved for at least some orbits with smaller sets of well defined points (Albertz *et al.*, 2005).

Absolute Fit of Standard HRSC DTM to MOLA DTM

The topography described by the results of the MOLA instrument provides the best available control for height accuracy. As described before, the HRSC DTMs had to be converted to the height reference of MOLA before comparison. Then, absolute offsets of height, determined as average deviation between the Level-4 DTM and MOLA heights, are of the following magnitude:

- approximately 80 percent orbits with height offsets less than 200 m,
- approximately 60 percent orbits with height offsets less than 100 m, and
- approximately 45 percent orbits with height offsets less than 50 m.

The comparison of these values with the previously shown relative accuracies shows a typical advantage of the symmetrical arrangement of HRSC's stereo sensors: in spite of reduced interior accuracy, obviously caused by erroneous pointing or camera/spacecraft alignment information, the values for absolute accuracy of height, derived by the entire set of symmetrically arranged stereo CCD lines, can be at least of the same quality as the interior accuracy or even better. Nevertheless, erroneous orbital height information can only be corrected by additional information (e.g., by bundle block adjustment with absolute height control).

The quality assessment of the absolute lateral accuracy of products is more complex and depends strongly on the actual state of the orientation data (orbit, pointing, and timing) which are available at the time of processing. If processing is based on reconstructed orbit data and accurate spacecraft clock information, lateral offsets to the MOLA DTM are limited to a few hundred meters, while nominal MEX orbit information may be off the reference by more than a kilometer.

Table 1 summarizes the HRSC standard data products quality and availability under operational aspects. Further quality improvements of products can be expected by systematical integration of bundle block adjustment results, i.e., adjusted exterior orientation yielding enhanced absolute registration to the MOLA DTM as reference topography (see Albertz *et al.*, 2005).

Extended Photogrammetric Data Processing

While standard Level-4 generation is focusing on fast availability of map projected image and 3D data products, more extended and dedicated data analysis has to be applied in order to derive higher resolution photogrammetric products for specific targets and to comply with the specific requirements of the great variety of different targeted investigations within the HRSC Co-Investigator Team.

One example of non-standard processing requirements is given by the generation of HRSC topographic image maps in scales of up to 1:100 000, where visual image representation is the primary goal. Printed maps, even in these large scales, often cover areas of different orbits. Thus, image mosaicing is required to derive a homogeneous representation. Other investigations require information about illumination and observation directions of each Level-4 pixel, or, for the combination of HRSC topography with the MOLA data set, 3D object point files including accuracy information. Due to the special geometric characteristics of non-standard HRSC observations of Mars (e.g., limb scans for atmospheric studies or observations of the Martian satellites) photogrammetric processing for the derivation of DTM and orthoimage products for these data also requires a special treatment.

More detailed stereo processing, involving also additional procedures and developments, is a subject of current investigations. On the other hand, variations in the procedural assembly of the standard processing steps are experimented, such as image matching extended to all reasonable stereo-combinations including simple double-stereo (i.e., additional correlation of both pairs of forward and backward looking stereo sensors). These experiments have already allowed for the derivation of significantly higher DTM resolutions and are (and must be) carried out in conjunction with validation studies addressing the statistical justification of and quantitative quality indicators relevant to a given resolution of derived data products. Although extended processing generally requires additional efforts for data evaluation, it is nevertheless based on widely automated processes and can typically be performed within days or few weeks.

TABLE 1. SUMMARY OF HRSC STANDARD PRODUCTS

Processing Level	From MOLA (based on reconstructed MEX orbit data)	Availability After Download of Raw Data
Level-2 (calibrated image data)	-(no geometric correction)	1 day
Level-3 (map projected image data)	500 m lateral	1 day
Level-4, 3D data (raster DTM)	100 m vertical 500 m lateral	2–3 days
Level-4, image data (ortho-rectified image data)	500 m lateral	3 days

Conclusions

Within the HRSC/SRC ground data processing system automated procedures have been set up and are applied on an operational base for the derivation and provision of high-resolution, multi-spectral, multi-phase and 3D data products in resolutions of 10 m to 200 m within a very short time frame. The provided photogrammetric products show that, in agreement with the results of accuracy analysis reported by Albertz *et al*. (2005), 3D accuracies significantly better than 200 m are achieved for many MEX orbits. Standard processing, together with results of current studies by the MEX HRSC Photogrammetry and Cartography Working Group, will further add to the achievements of the mission for the benefit of geoscientific research.

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