The High Resolution Stereo Camera (HRSC) of Mars Express and its approach to science analysis and mapping for Mars and its satellites

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The High Resolution Stereo Camera (HRSC) of ESA’s Mars Express is designed to map and investigate the topography of Mars. The camera, in particular its Super Resolution Channel (SRC), also obtains images of Phobos and Deimos on a regular basis. As HRSC is a push broom scanning instrument with nine CCD line detectors mounted in parallel, its unique feature is the ability to obtain along-track stereo images and four colors during a single orbital pass. The sub-pixel accuracy of 3D points derived from stereo analysis allows producing DTMs with grid size of up to 50 m and height accuracy on the order of one image ground pixel and better, as well as corresponding orthoimages. Such data products have been produced systematically for approximately 40% of the surface of Mars so far, while global shape models and a near-global orthoimage mosaic could be produced for Phobos. HRSC is also unique because it bridges between laser altimetry and topography data derived from other stereo imaging instruments, and provides geodetic reference data and geological context to a variety of non-stereo datasets. This paper, in addition to an overview of the status and evolution of the experiment, provides a review of relevant methods applied for 3D reconstruction and mapping, and respective achievements. We will also review the methodology of specific approaches to science analysis based on joint analysis of DTM and orthoimage information, or benefiting from high accuracy of co-registration between multiple datasets, such as studies using multi-temporal or multi-angular observations, from the fields of geomorphology, structural geology, compositional mapping, and atmospheric science. Related exemplary results from analysis of HRSC data will be discussed. After 10 years of operation, HRSC covered about 70% of the surface by panchromatic images at 20 m/pixel, and about 97% at better than 100 m/pixel. As the areas with contiguous coverage by stereo data are increasingly abundant, we also present original data related to the analysis of image blocks and address methodology aspects of newly established procedures for the generation of multi-orbit DTMs and image mosaics. The current results suggest that multi-orbit DTMs with grid spacing of 50 m can be feasible for large parts of the surface, as well as brightness-adjusted image mosaics with co-registration accuracy of adjacent strips on the order of one pixel, and at the highest image resolution available. These characteristics are demonstrated by regional multi-orbit data.
1. Introduction

Among the various experiments that have imaged (or still are imaging) the surface of Mars and its satellites, the High Resolution Stereo Camera (HRSC; Neukum and Jaumann, 2004; Jaumann, 2007) of the Mars Express mission is unique in terms of its imaging principle, in that concomitant digital terrain models (DTMs) and multiple orthoimages (which already cover a high percentage of the surface of Mars) can be derived based on its standard mode of operation, and in its specific geometric resolution. Moreover, an additional Super Resolution Channel (SRC) provides co-aligned images at approximately 5 times higher resolution (Oberst et al., 2008). The geometric resolution of HRSC falls in between of the global geodetic reference dataset provided by the Mars Orbiter Laser Altimeter experiment (MOLA; Smith, 2001) and the globally available Mars stereo image datasets providing still higher ground resolution. HRSC's along-track stereo imaging principle supports the provision of concomitant image and DTM coverage by enabling continuous acquisition of stereo images on a single orbital pass.

HRSC is the only experiment in planetary exploration that employs a sensor system specifically designed for extraterrestrial photogrammetric mapping (Albertz, 2005), with the exception of the recent mapping missions to the Moon (e.g. Haruyama et al., 2012). HRSC is a multi-line pushbroom stereo camera providing up to 5 panchromatic multi-angle observations during a single orbital pass while achieving a nominal ground resolution of up to 10 m (Jaumann, 2007; see also Table 1). Simultaneously, multi-spectral images are acquired by 4 CCD lines equipped with spectral filters (near-infrared, red, green, blue). HRSC data are unique in covering very large areas (typically on the order of 10^4 to 10^5 km^2) in stereo and color with a single imaging sequence (or image strip), i.e. a set of HRSC stereo and color images acquired on one orbital pass. A comprehensive set of processing techniques is applied to produce high-resolution DTMs (up to 50 m grid spacing) and corresponding orthoimages (up to 12.5 m/pixel) as the central high-level products covering the MC-11 (East) quadrangle of Mars, representing the first prototype of a new HRSC data product level.

After ten years in Mars orbit, surface coverage in general as well as of surface features is abundant. At this point in time, the goal of global 3D-mapping of Mars has assumed a central role for the experiment. Integrating data from multiple orbits into mosaics and multi-orbit DTMs, as demonstrated for the final landing site candidates of the Mars Science Laboratory (MSL) mission (Gwinner et al., 2010b, see also Fig. 41), including the finally selected site (Gale crater, Fig. 1), offers evident advantages for data handling and analysis. Similarly, based on the comprehensive dataset aggregated through a large number of opportunities to observe the Martian satellites, a new control point network and shape model (Willner et al., 2013) and a first near-global controlled orthoimage mosaic (Wählisch et al., 2014) could be derived for Phobos (see Fig. 39, Section 5.1).

Three-dimensional data products derived from planetary images are increasingly available and have allowed new, sometimes spectacular insights concerning the surface morphology of planets, moons and asteroids in the solar system. Examples include the unexpected interior topography of the Caloris basin on Mercury (Oberst et al., 2010) revealed by stereo-derived DTMs from images of the Mercury Dual Imaging System (MDIS; Hawkins, 2007; Solomon et al., 2008), the surprisingly large depth of Mercury's pit craters, derived from stereo images of the same instrument (Gwinner et al., 2012), morphological details of the surface of asteroid Vesta evident from the DAWN mission such as steep surface features.

### Table 1

<table>
<thead>
<tr>
<th>HRSC SRC main characteristics and baseline performance.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electro-optical performance</strong></td>
</tr>
<tr>
<td><strong>Optics</strong></td>
</tr>
<tr>
<td>HRSC: Apo-Tessar</td>
</tr>
<tr>
<td>SRC: Matsukov-Cassegrain telescope</td>
</tr>
<tr>
<td><strong>Focal length</strong></td>
</tr>
<tr>
<td>HRSC: 175 mm</td>
</tr>
<tr>
<td>SRC: 985 mm</td>
</tr>
<tr>
<td><strong>Focal ratio</strong></td>
</tr>
<tr>
<td>HRSC: f=5.6</td>
</tr>
<tr>
<td>SRC: f=11</td>
</tr>
<tr>
<td><strong>Along-track stereo angles</strong></td>
</tr>
<tr>
<td>S1: +18.9°, P1: +12.8°,</td>
</tr>
<tr>
<td>ND: 0°, P2: -12.8°, S2: -18.9°</td>
</tr>
<tr>
<td><strong>Detector type</strong></td>
</tr>
<tr>
<td>HRSC: THX 7808B</td>
</tr>
<tr>
<td>SRC: Kodak KAI 1001</td>
</tr>
<tr>
<td><strong>Sensor pixel size</strong></td>
</tr>
<tr>
<td>HRSC: 7 μm x 7 μm</td>
</tr>
<tr>
<td>SRC: 9 μm x 9 μm</td>
</tr>
<tr>
<td><strong>Field of view per pixel</strong></td>
</tr>
<tr>
<td>HRSC: 5 arcsec</td>
</tr>
<tr>
<td>SRC: 2 arcsec</td>
</tr>
<tr>
<td><strong>Active pixels per sensor</strong></td>
</tr>
<tr>
<td>HRSC: 8 × 8</td>
</tr>
<tr>
<td>SRC: 9 × 9</td>
</tr>
<tr>
<td><strong>Radiometric resolution</strong></td>
</tr>
<tr>
<td>HRSC: 8 bit before compress.</td>
</tr>
<tr>
<td>SRC: 14 bit or 8 bit selectable</td>
</tr>
<tr>
<td><strong>Sensor full well capacity</strong></td>
</tr>
<tr>
<td>HRSC: 420,000 e</td>
</tr>
<tr>
<td>SRC: 48,000 e</td>
</tr>
<tr>
<td><strong>Signal chain noise</strong></td>
</tr>
<tr>
<td>HRSC: &lt; 42 e (rms)</td>
</tr>
<tr>
<td>SRC: &lt; 42 e (rms)</td>
</tr>
<tr>
<td><strong>Gain attenuation range</strong></td>
</tr>
<tr>
<td>HRSC: 3.5–2528 (10.5–62 dB)</td>
</tr>
<tr>
<td>SRC: 3.5–2528 (10.5–62 dB)</td>
</tr>
<tr>
<td><strong>Spectral filters</strong></td>
</tr>
<tr>
<td>HRSC: 5 panchromatic, 4 color</td>
</tr>
<tr>
<td>SRC: panchromatic</td>
</tr>
<tr>
<td><strong>Nadir channel (ND), 4x off-nadir (S1,S2,P1,P2)</strong></td>
</tr>
<tr>
<td>HRSC: 675 ± 90 nm</td>
</tr>
<tr>
<td>SRC: –</td>
</tr>
<tr>
<td><strong>Blue (BL), green (GR), red (RE), near-infrared (IR)</strong></td>
</tr>
<tr>
<td>HRSC: 440 ± 40 nm</td>
</tr>
<tr>
<td>SRC: –</td>
</tr>
<tr>
<td><strong>Pixel exposure time</strong></td>
</tr>
<tr>
<td>HRSC: 2.24 ms to 54.5 ms</td>
</tr>
<tr>
<td>SRC: 0.5 to 516 ms</td>
</tr>
<tr>
<td><strong>Pixel summation formats</strong></td>
</tr>
<tr>
<td>HRSC: 1 × 1, 2 × 2, 4 × 4, 8 × 8</td>
</tr>
<tr>
<td>SRC: –</td>
</tr>
<tr>
<td><strong>Pixel size on ground</strong></td>
</tr>
<tr>
<td>HRSC: 10 m × 10 m @250 km</td>
</tr>
<tr>
<td>SRC: 2.3 m × 2.3 m @250 km</td>
</tr>
<tr>
<td><strong>Image size on ground</strong></td>
</tr>
<tr>
<td>HRSC: 522 km swath x [time]</td>
</tr>
<tr>
<td>SRC: 2.35 km x 2.35 km @250 km</td>
</tr>
<tr>
<td><strong>Compression rates</strong></td>
</tr>
<tr>
<td>HRSC: nominal: 5 to 10</td>
</tr>
<tr>
<td>SRC: not applied</td>
</tr>
<tr>
<td><strong>Typ. data vol. per image</strong></td>
</tr>
<tr>
<td>HRSC: 250 Mbit</td>
</tr>
<tr>
<td>SRC: 8 Mbit or 14 Mbit</td>
</tr>
</tbody>
</table>

* Longer exposure times technically feasible, but not realized due to dark current.
slopes, asymmetric impact craters, and spiral-shaped mass wasting features (Jaumann, 2012), the Global Lunar DTM (GLD100, Scholten et al., 2012) computed from images of the wide-angle camera of the Lunar Reconnaissance Orbiter Camera (LROC; Robinson, 2010), which was never designed to provide stereo capabilities, and a variety of small scale morphological features in DTMs derived from LROC-NAC images (Watters et al., 2010), the High Resolution Imaging Science Experiment of Mars Reconnaissance Orbiter (MRO/HiRISE; McEwen et al., 2007; Kirk et al., 2008), and HRSC (Gwinner et al., 2009). In addition to DTMs, stereo images allow the derivation of further valuable data products such as orthorectified images, which also provide manifold capabilities for mapping and science analysis related to surface, atmospheric, and astrometric studies. For example, stereo images have significantly contributed to estimates of the shape, rotation, spins axis orientation and volume of celestial objects (e.g., Jaumann et al., 2012; Russell, 2013; Oberst et al., 2014).

The stereo capabilities of HRSC are based on the along-track multi-stereo concept (Hofmann et al., 1982), which has been further investigated in various Earth-oriented applications before the launch of Mars Express (e.g., Ebner et al., 1996; Wewel et al., 2000; Gwinner et al., 2000) and during the early mission phases, using the first data of Mars Express HRSC (Ebner et al., 2004; Scholten et al., 2005; Kirk et al., 2006; Jaumann, 2007; Heipke et al., 2004, 2007; Spiegel, 2007a, 2007b; Gwinner et al., 2009). Specifically, along-track stereo allows for near-simultaneous acquisition of stereo images. This offers major benefits for data analysis since changes of the illumination and atmospheric conditions are avoided. Employing several stereo sensors mounted in parallel allows for acquisition of multiple stereo images as standard with low operational efforts. In the case of HRSC, line sensors operated in pushbroom mode are employed and no spacecraft pointing or platform tilts are required to obtain stereo views. The various experimental studies that have been devoted to HRSC stereo analysis have also fed into a systematic comparison test (Heipke, 2007). The comparison test represents a unique endeavor among the planetary imaging experiments and has significantly contributed to consolidate the methodology applied for systematic generation of photogrammetric data products for HRSC (Gwinner et al., 2008, 2010a).

The various missions to Mars to date have provided abundant stereo images, which are in part of still higher resolution than those of HRSC. The Viking mission already provided global coverage by stereo images, although at low resolution, and produced high-resolution datasets only locally (Kirk et al., 1999). Similarly, Mars Global Surveyor (MGS) provided stereo pairs with its narrow-angle device for selected areas of interest only (Malin and Edgett, 2001; Kirk et al., 2003; Yoon and Shan, 2005). The HiRISE and the Context Camera (CTX; Malin et al., 2007) experiments onboard MRO are acquiring stereo images of up to 0.3 m and a few meters ground pixel size, respectively, but again for limited areas of only <1% and <10% of the surface, respectively. Thus, except for the HRSC products, none of the available stereo datasets provides a basis for global mapping at high spatial resolution.

The concomitant image and DTM coverage of HRSC offers a straightforward link to the global MOLA reference both for stereo and non-stereo datasets. The latter include the majority of the above-mentioned datasets and, in addition, panchromatic, multispectral and spectroscopic data sets from instruments providing global coverage for Mars such as the Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité de Mars Express (OMEGA, Bibring et al., 2006) or the Compact Reconnaissance Imaging Spectrometer for Mars of MRO (CRISM; Murchie, 2007). Due to its ground resolution and concomitant DTM coverage, HRSC is also designed to support context studies for these instruments (see also Jaumann et al., 2015).

This paper, in addition to providing an updated overview of the status and evolution of the experiment, focuses on the specific capability of HRSC to provide precise topographic information by means of stereo observation and analysis. HRSC topographic data products, more specifically, include high-resolution DTMs and orthoimages derived from the nadir, color, and panchromatic multi-angle observations of HRSC, which are precisely co-registered to the DTM.

Many studies have exploited this information, applying their task-specific methodology. In particular, large coverage and DTMs provide a unique data base for geodesy and geomorphology. There is also a range of other applications, including studies that make use of geometrically precise color and multi-angle observations, as well as co-registered multiple image coverage. We will explain how such methods are applied to serve central mission goals of Mars Express and other missions, such as photogeologic exploration, the study of surface-atmosphere interactions, mineralogical mapping, landing site analysis, as well as emerging topics such as detecting and characterizing local changes occurring at or near the surface of planetary bodies to understand ongoing dynamic phenomena. The capabilities of such methods are discussed in relation to the characteristics of the instrument and major evolutionary steps and operational achievements of the experiment (see also Jaumann, 2007), in particular in relation to the topographic data products derived from HRSC data (Sections 2 and 3). For this purpose, we will make reference to exemplary studies completed within ten years of application in Mars orbit and from different areas (Sections 4 and 5), without claiming to offer an exhaustive review of all relevant previous work. Section 5 offers a reports on accomplishments in two exemplary use cases (Martian satellites observations and landing site characterization), which were selected due to the diversity of data product types and applied methods these studies involve. We will also present and use original results of recent work on bundle block adjustment, and on the generation of multi-orbit DTMs and brightness-adjusted image mosaics, including their evaluation, which has led to the definition of a new HRSC data product level and to the completion of a corresponding first mapping tile of the global MC-30 mapping scheme of Mars, covering quadrangle MC-11 (East) (Section 3).

2. HRSC mission dataset, calibration and recent data quality improvements

2.1. Instrument characteristics and status

The HRSC instrument (Fig. 2) represents a multi-sensor pushbroom camera comprising 9 CCD line sensors mounted in parallel for simultaneous acquisition of stereo and color image swaths (Neukum and Jaumann, 2004; Jaumann, 2007). The CCD arrays provide 5184 active pixels and share the same transmissive optics, which comprises an Apo-Tessar lens design with a focal length of 175 mm. Fig. 2 provides an illustration of the along-track stereo imaging principle applied, and shows the viewing directions of the five panchromatic channels used for stereo imaging (ND – nadir channel, S1 and S2 – stereo channels, P1 and P2 – photometry channels). The four color channels (BL – blue, GR – green, RE – red, IR – near infrared, not represented in Fig. 2) are observing at off-nadir angles in between the viewing angles of each pair of adjacent panchromatic channels. The additional super resolution channel (SRC) of the camera system provides co-aligned frame images at an approximately 5 times higher resolution (Oberst et al., 2008). SRC comprises a 1024 × 1024 CCD array and lightweight mirror optics (Maksutov-Cassegrain telescope) with a focal length of 985 mm. Table 1 lists the technical specifications of
HRSC and SRC relevant to this paper. A comprehensive technical description of the instrument was provided in Jaumann (2007).

Radiometrically calibrated HRSC data (Level-2 data), Level-4 data (high-resolution DTMs and orthoimages) and ancillary data are available via the PSA (Planetary Science Archive) and PDS (Planetary Data System) catalogs [www1, www2]. In addition, so-called map-projected images (Level-3 data) are available in these archives. In contrast to the Level-4 orthoimages, where the corresponding HRSC DTM is used for rectification, rectification of Level-3 images is based on the terrain representation provided by the MOLA DTM.

After more than 10 years of operations in orbit around Mars, the HRSC camera instrument including the SRC is fully functional without any noticeable signs of degradation. In May 2013, SRC routine operations could be restored after a hiatus of almost two years, due to anomalies associated with the Mars Express Solid State Mass Memory (SSMM) that triggered several safe modes and a general stop of science operations on August 23, 2011. After switching to the redundant SSMM and power supply systems, the number of parallel and multiple observations per orbit and the number of commands necessary for operations had to be reduced drastically. New command sequences were defined and implemented as On Board Control Procedures (OBCPs). In addition, the Mars Express mission operations concept was modified to better handle SSMM anomalies and to avoid related safe modes. After OBCP implementation and testing of the new concept, Mars Express returned to nearly routine science operations in early 2012 but the work in OBCP implementation continued until the beginning of 2013.

As the SRC was added rather late in the HRSC design, a redundant power supply was not implemented and SRC was the last item on Mars Express still out-of-operations. By setting an internal HRSC relay in its on-state, however, it was possible to bypass the problem and restore SRC routine operations. Changing the state of the relay required HRSC to be powered once more on the nominal branch. Fortunately, the entire procedure had already been successfully demonstrated on Earth with the fully integrated Mars Express spacecraft during thermal-vacuum tests.

### 2.2. Updates to the radiometric calibration of HRSC based on in-flight data

The radiometric calibration of HRSC is primarily based on an extensive set of on-ground laboratory measurements (Jaumann et al., 2007). After radiometric correction, HRSC image data are given in radiance units as well as units of I/F corresponding to the “radiance factor” as defined by Hapke (1993), i.e. the ratio of the surface reflectance as measured and the reflectance of a perfectly diffuse surface illuminated at 90° solar elevation. This includes the correction of signal level differences between odd and even branches of each CCD sensor in cases when it is operated without pixel binning and correction for pixel response non-uniformity (“flat-field” correction).

While an initial calibration from on-ground measurements (including dark signal, blemish pixels, pixel response non-uniformity, and gain factors) was used before Mars orbit insertion, a final laboratory-based calibration version was completed in May 2004. Further refinement of flat-field and gain factor calibration was achieved by analysis of suitable in-flight images. The updates

![Fig. 2: The HRSC/SRC instrument with digital unit (left), camera head with sensor electronics (middle), and optics for the HRSC (with baffle, upper right) and SRC (lower right). Bottom: Multi-line stereo imaging principle of HRSC, arrow symbolizes spacecraft motion. Only the 5 panchromatic stereo channels are depicted (ND – nadir channel, S1 and S2 – stereo channels, P1 and P2 – photometry channels).](image)

<table>
<thead>
<tr>
<th>Date of calibration version</th>
<th>Property changed/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-05</td>
<td>Final version of the laboratory-based calibration</td>
</tr>
<tr>
<td>2004-11</td>
<td>Improved flat-fields for sensors BL, GR, S1, S2, based on in-flight images (on-ground calibration equipment had caused a gradient in the flat-field)</td>
</tr>
<tr>
<td>2005-08</td>
<td>Improved flat-fields for all sensors, based on in-flight images until orbit 2000</td>
</tr>
<tr>
<td>2005-11</td>
<td>Improved gain factors, based on in-flight images</td>
</tr>
<tr>
<td>2008-04</td>
<td>Improved flat-fields for all sensors, based on in-flight images. Gradient in flat-fields due to solar azimuth in selected calibration images removed.</td>
</tr>
<tr>
<td>2008-05</td>
<td>Improved gain factors, separately for each signal chain, based on in-flight images. Additional non-linear gain factor, depending on exposure time.</td>
</tr>
<tr>
<td>2008-09</td>
<td>Further update of gain factors.</td>
</tr>
<tr>
<td>2014-12</td>
<td>Further update of gain factors, based on “broom calibration” images of Mars which offer nearly identical viewing geometry for each image channel.</td>
</tr>
</tbody>
</table>
based on in-flight data consist of relative corrections of calibration parameters with changes on the order of a few percent. The conversion to units of spectral radiance, on the contrary, is still entirely based on laboratory measurements using an absolute brightness standard. The update history of the radiometric calibration of HRSC based on in-flight data, starting in November 2004, is given in Table 2. In parallel to successive updates, each of the versions listed in the table was applied to the images included in the released data records during the respective time interval. In 2008, a complete reprocessing of all released calibrated HRSC images was performed on the basis of calibration version 2008-09, and in 2014 a complete reprocessing was performed based on version 2014-12, which is currently in use.

Refinement of the calibration using in-flight data was attempted first to remove artificial brightness gradients along image lines observed in images from Mars orbit, which presumably was caused by the on-ground calibration equipment used. Due to an initial lack of good calibration images, in particular concerning solar azimuth, three related updates to the flat-fields have been issued, until a satisfactory result was finally reached with calibration dataset version 2008-04. The refinement was based on regular mapping images of the Mars surface, where prominent surface features of extent approaching the scale of the image width were avoided and systematic variation of brightness related to each CCD pixel was determined statistically from a large number of image lines. In Fig. 3, the brightness gradients are displayed as color gradients for three of the panchromatic channels, and their removal can be demonstrated.

Furthermore, in-flight data suggested small errors in the gain factors associated with different integration times and the four signal chains of the instrument. These were noted at integration time switches commanded within the same image strip, and correction factors could be derived for the relative adjustment of the small resulting brightness differences based on the statistical properties of adjacent image areas. Specific observations from high altitudes and involving spacecraft slews (in the following called “broom calibration” images) were acquired in 2013 and 2014 (see also Section 2.6 and Fig. 11) providing images with nearly identical conditions and viewing angles for re-analysis of system gain, which lead to a further refinement of the gain factor calibration (version 2014-12).

The broom calibration technique allows us to determine small gain factor differences for the four parallel signal chains of HRSC since the ground pixel size of these images is large (on the order of 1–10 km/pixel) and, accordingly, topography-related effects are small. Furthermore, the viewing directions differ by less than 2° for all nine image channels, and each set of calibration images was acquired within a time interval of less than 5 min. The images are orthorectified using the MOLA DTM, and very dark areas close to terminator crossings are excluded. Fig. 4 shows an example of the
intensity histograms and average intensities for four calibration images. Intensity is normalized to the intensity of the fifth panchromatic image, the nadir image. A Gaussian is fitted to the histogram of each of the normalized panchromatic images to estimate the relationship between their intensity distributions in terms of a correction factor, which is determined from all histograms of all calibration orbits simultaneously. The residual differences of the adjusted average intensities seen in the example of Fig. 4 represent the calibration orbits simultaneously. The residual differences of the correction factor, which is determined from all histograms of all calibration images, average intensities for four calibration images. Intensity is normalized to the intensity of the intensity histograms and average intensities for four calibration images. Intensity is normalized to the intensity of the fifth panchromatic image, the nadir image. A Gaussian is fitted to the histogram of each of the normalized panchromatic images to estimate the relationship between their intensity distributions in terms of a correction factor, which is determined from all histograms of all calibration orbits simultaneously. The residual differences of the adjusted average intensities seen in the example of Fig. 4 represent the uncertainty related to the set of new gain calibration factors. Uncertainty is related to the radiometric precision of the images (image noise, residual flat field effects) and to existing deviations from an ideal set of calibration images (accuracy of co-registration, sampling effects, resampling applied during orthorectification). For all calibration images, average intensity (in digital numbers) of the stereo images is plotted against average intensity of the corresponding nadir image in Fig. 5, where the situation before and after applying the new gain factors can be compared. We note a shift of the channel ratios towards unity (dashed line), demonstrating improved consistency between the channels for high as well as lower signal levels. Correspondingly, the spread of the average channel ratios reduces from 0.023 (1σ) with the previous calibration version to 0.011 with version 2014–12.

Because the images have been acquired under nearly identical conditions, the variance of the Gaussian fits to the normalized intensity histograms provides an upper limit for estimating the radiometric precision of panchromatic HRSC images. The standard deviation of 1.5%, on average (median: 1.5%), represents a conservative estimate for the relative error of the radiometric calibration at full image resolution, derived from actual mission data. Applications which highly depend on precise intensity data (see, e.g., Section 4.6) often work with images at reduced spatial resolution because the effects of the error sources mentioned above can be expected to decrease. For the set of calibration images, the standard deviation reduces to 0.98%, on average (median: 0.84%), when image scale is reduced by a factor of 10, i.e., when each intensity value represents an average of 100 original pixel samples.

2.3. Geometric calibration of HRSC and SRC

During the mission, the geometric calibration data for HRSC which had been determined initially by pre-launch laboratory measurements (Jaumann, 2007) were checked and improved using stereo-photogrammetric adjustment based on in-flight data (Spiegel 2007a, 2007b). Using 46 selected orbits, systematic errors in the image coordinates of tie-points (points visible in various images) were removed by improving the image coordinates of the principal point in a self-calibration bundle adjustment (see also Section 3). Correction values were introduced for seven of nine HRSC sensors, according to the statistical significance level of the estimated changes. The two remaining sensors as well as the nominal focal length were kept fixed. The metric deviations within the focal plane, as compared to the pre-launch calibration, reach up to 6.7 μm (i.e. 0.96 pixels) for the panchromatic sensors. The respective effect on the 3D point accuracy was also assessed (Spiegel, 2007a, 2007b), where an improvement of 10–15% was reported. For the color sensors, the corrections within the focal plane reach up to 9.5 μm (i.e. 1.4 pixels). The updated geometric calibration has been applied to all derived HRSC products released through PSA and PDS.

The focal length of SRC was determined before launch at 975.0 mm while the analysis of star field observations during cruise pointed to a higher value of 983.5 mm (Oberst et al., 2008). Based on the matching of Mars surface features represented in SRC imagery with HRSC data, Oberst et al. (2008) derived a relative magnification factor of SRC as compared to HRSC of 4.33 and an associated SRC focal length of 988.5 mm. This value was used for the geometric calibration of SRC before December 2013. In 2013, the camera was pointed towards the Pleiades star field in orbit 11964 (29 May 2013) and acquired a sequence of 145 SRC images to verify its internal geometry and to monitor pointing oscillations by the spacecraft. Another 45 images were acquired at different exposure times to better constrain the SRC sensitivity and point spread function (PSF). After re-evaluation of the SRC geometric calibration based on these data, refined alignment angles of the camera with the spacecraft coordinate system and with HRSC could be derived and its focal length was computed to be 984.76 mm (T. Duxbury, personal communication), quite consistent with the in-flight star observations during cruise by Oberst et al. (2008). In December 2013, these parameters were updated in the SRC instrument and frame kernels and thus are officially used in the geometric calibration.

2.4. SRC Image enhancements

Oberst et al. (2008) demonstrated a distortion of the optics of SRC, seen in images as blurring and ghosting (Oberst et al., 2008). The analysis of star images demonstrated that the PSF was asymmetrical, with offset secondary intensity peaks, and spreading of intensity...
mostly within a radius of 5 pixels (Fig. 6, left). Owing to mass constraints, the SRC optics had to be designed with limited light gathering power (f/11) from the outset. With a typical Mars ground track velocity of 3.5 km/s at closest approach where the ground resolution is 2.4 m/pixel, an exposure time of 0.6 ms would be required to avoid motion-smear. An acceptable SNR is achieved at much higher exposure times, and the optimal trade-off for the imaging conditions of the Mars surface has been found to be around 5 ms which results typically in a motion smear of 5–10 pixels in flight direction. Although the pixel scale of the motion smear is similar to that of the optical distortion, the degree of image degradation is less because of its one-dimensional nature: the brightest pixels of the smear PSF collect around 8% of the light from a point source. Fig. 6 (right) shows the compounded effect of the two distortions.

A Richardson–Lucy deconvolution algorithm is applied to compensate for these distortions. The quality of the result depends on the level of noise in the image, its dynamic range, and the precision of the PSF. The deconvolution enhances noise which, where identifiable, can be removed by replacing pixels in a 3 × 3 neighborhood which differ from the local median by more than some threshold value. Images with very low dynamic range may contain “flat” areas of near-constant DN value. Attempts at enhancement tend only to introduce artefacts at the boundaries between the flat areas. Thus, we have more success with higher

![Fig. 6. Left: Central part of the point spread function of SRC representing consequence of thermal optics distortion derived from stacked star images (T. Duxbury, pers. comm.) Dimensions of the full PSF array 21 × 21. Right: Thermal optics distortion combined with typical motion smear component. Numbers indicate the percentage of light from a point source falling into local pixels.](image)

![Fig. 7. Mars surface: 400 pixels wide crop from SRC image 4199_0002 a) in raw form, and b) after enhancement. c) Equivalent region in HRSC image.](image)
dynamic range images in need of more deconvolution than low dynamic range images even if less distorted. This is the basis for the exposure trade-off. Richardson–Lucy deconvolution is an iterative procedure: eventually, a trade-off between enhanced detail and increased noise determines how far the improvement can be taken. We have found that Mars surface images are more challenging to recover than Phobos images as the former show smaller contrast in general. Nevertheless, we have processed 239 SRC mosaics (usually sequences of 7 images) of the Mars surface which offer a perceived resolution improvement over HRSC by a factor of 2–3 (e.g. Fig. 7). Phobos, on the other hand, because of its lack of atmosphere, yields much higher contrast images, which are more amenable to the deconvolution.

2.5. Spacecraft attitude and pointing stability

For the derivation of DTMs and orthoimages, the knowledge of position and attitude of the camera is essential. The spacecraft position is observed via Doppler measurements; star trackers determine the attitude of the spacecraft (Lauer et al. 2004; Landi et al. 2006) and thus, combined with alignment information, that of the camera. The set of spacecraft position, pointing, and alignment data is called the nominal exterior orientation of the camera and is provided by ESA (European Space Agency). The quality of the nominal exterior orientation is generally not sufficiently accurate for precise photogrammetric point determination by the given high-resolution sensor system. The nominal pointing of the Mars Express spacecraft is accurate to 0.025° for all three pointing angles (Lauer et al., 2004). The accuracy of orbit position in body-centered cartesian X, Y and Z co-ordinates is stated in ranges of 10–2120 m, 2.5–795 m, and 1–80 m, respectively, where orbit reconstruction depends on a number of factors such as the number and quality of Doppler measurements and the number of receiving ground stations (Hechler and Yáñez, 2000). Therefore, stereo-photogrammetric techniques are applied for the improvement of the spacecraft position and pointing for each HRSC imaging sequence. In terms of absolute values, and for the entire set of fully stereo-processed image strips, the resulting average corrections for orbit position amount to 105 m along track, 100 m across-track, and 45 m for the vertical component. For about 50% of the orbits the corrections are smaller than 200 m along-track, 200 m across-track, and 100 m vertically (Gwinner et al., 2010a). The average angular corrections are typically 0.011° along-track (pitch), 0.007° across-track (roll), and 0.008° for spacecraft yaw. With respect to the mean HRSC pixel scale of 15 m and the IFOV of 0.00229°, the corrections correspond to approximately 3–7 pixels. These values may be exceeded in exceptional cases (i.e. on the order of 1 km), for example in the case of degraded Doppler tracking or insufficient star visibility for the star trackers.

In addition to the typical random deviations of the true pointing from the nominal exterior orientation data, photogrammetric techniques are also able to determine and correct for systematic spacecraft attitude variations that are of much higher frequency than typical deviations (see Fig. 15, Section 3.1). Such oscillations can attain significant amplitudes and have been detected for a considerable number of HRSC image strips (Gwinner et al., 2010a). The effect can be corrected using the sequential photogrammetric adjustment procedure (SPA; Gwinner et al., 2010a) or bundle adjustment (Bostelmann and Heipke, 2011; see also Section 3.1). We note that these techniques are based on rigorous 3D modeling of the process, as opposed to relative adjustment of line jitter effects applied in the image plane only.

The spacecraft oscillations are obviously caused by mechanical effects such as movements of the solar panels that result from spacecraft maneuvers. In extreme cases, which occur primarily immediately after such maneuvers, the magnitude of the oscillations rises to 0.03° (double amplitude) and higher, i.e. an angular deviation more than 10 times larger than the IFOV of HRSC. Although the amplitude decreases significantly within a few minutes, stereo analysis of HRSC data has revealed residual oscillations up to 10 min after the maneuver, and later in exceptional cases. The amplitude is typically much smaller by then, often at or below the HRSC pixel scale, which nevertheless still can be determined by stereo-photogrammetric analysis. In either case, the frequency has been very constant during all mission phases, i.e. 0.12±/− 0.005 Hz.

Fig. 8 displays an example of oscillations, which appear in the spacecraft housekeeping data as angular deviations of the Mars Express star tracker camera from its nominal position (Fig. 8, left) and have led to corrections derived by photogrammetric techniques for the three nominal pointing angles of an HRSC imaging sequence acquired during the respective period (Fig. 8, right).
that active spacecraft pointing, based upon the star tracker information, is typically afflicted with some delay. Thus, the derived corrections are not identical to the housekeeping data but describe the same oscillation that has been initiated by the spacecraft maneuver.

Oscillations of the spacecraft in pointing are also of major concern for the astrometric measurements of the Martian moons based on SRC imagery which are described in more detail below. As a framing device, the SRC is geometrically stable in two directions and can measure directly pointing variations within its maximum frame rate of 1 image per 545 ms or nearly 2 Hz. High-frequency observations of the Phobos transit in front of Deimos or several planets were obviously affected by these pointing deviations. The observation of the Pleiades star field in orbit 11964 mentioned before was specifically designed to monitor spacecraft oscillations after having reached the requested pointing as shown in Fig. 9 for the x- and y-axes of the spacecraft. The x-axis of the graphs gives the SRC image number and the vertical lines indicate breaks in imaging to accommodate the data volume of this sequence. Time information is given in the top of each graph. The first two sets of images were recorded at highest imaging frequency, the next four sets of images at a 1 Hz frequency, while the last set was obtained at a frequency of one image per 2.1 s. Oscillations are most prominent around the x-axis of the spacecraft with an amplitude of more than 120 arcsec or 60 SRC pixels at the beginning and still about 50 arcsec or 25 SRC pixels after 3 min at a frequency similar to the one measured by the stereophotogrammetric analysis of HRSC data. It is also obvious that the available pointing information for the spacecraft does not properly reflect these oscillations. As a consequence, the waiting time of HRSC before image acquisition has been extended to at least four minutes after any MEX spacecraft pointing maneuver (whenever feasible within the available resources).

2.6. Evolution of observation conditions through time and status of data acquisition

After its successful Mars orbit insertion on December 25, 2003, Mars Express entered into a highly elliptical orbit and started with the commissioning of the instruments while the apoapsis was still lowered to reach the nominal mapping orbit. The first HRSC image in orbit around Mars was captured in orbit 8 on January 09, 2004 or at the end of Mars year (MY) 26 following the convention for a Mars calendar as introduced by Clancy et al. (2000). Since then, HRSC has been operating for more than 10 Earth years or more than 5 Martian years. An overview of its achievements until March 26, 2014 is given in Table 3. Fig. 10 depicts the characteristics and evolution of the Mars Express orbit in comparison with the HRSC imaging activities for mapping the Martian surface.

The major goal for HRSC is mapping the Martian surface globally at spatial resolutions preferably ≤ 20 m/pixel and in stereo. Global color coverage at lower spatial resolution is also achieved. Secondary targets are limb observations, clouds and atmospheric dynamics as well as the Martian moons. Consequently, HRSC imaging primarily occurs around periapsis, where spatial resolutions ≤ 20 m/pixel are achieved within a window of ± 7 min around the pericenter with the current orbit, while this window was ± 9 min at the beginning of the nominal mission (Pischel and Zeghers, 2009). Orbit inclination ensures that the sub-spacecraft point at pericenter passes through almost all latitudes and has meanwhile completed its migration from high southern to high northern latitudes and back more than 12 times since orbit insertion (Fig. 10a). Similarly, the periapsis drift provided a certain degree of variation in local time and season for each latitude after more than 5 MY (Fig. 10a and b).

HRSC is an optical instrument and operations are limited to daylight conditions (i.e., solar elevation angles above 0°). The orbit characteristics of Mars Express, however, were designed to meet the needs of all the instruments onboard with the optical instruments.
pericenter (Fig. 10d). Orbit inclination remained rather constant
were performed to improve nighttime conditions while later ones
optimize the illumination conditions at periapsis. Early orbit changes
mission mainly by lowering or increasing the apoapsis altitude to
fact, the nominal orbit was changed several times throughout the
within 86.5 – 86.9°. The revisit time of speciﬁc surface targets is a parameter of
major importance concerning the acquisition of image mosaics at
similar observing conditions and for multi-temporal observations.
The orbit resonance pattern deﬁnes the revisit time, i.e. the
number of orbits or days needed until the sub-spacecraft point at
periapsis returns (nearly) to the same longitude (see Fig. 10d). The
sub-pericenter points are grouped into longitudinal clusters
(Pischel and Zeghers, 2009). Initially, it took 13 orbits or 4 days to
have an adjacent ground track while today it takes 88 orbits or 25
days. The offset of adjacent ground tracks at periapsis was con-
trolled until 2010 in such a way that between ± 60° latitude HRSC
images obtained in nadir-pointing were overlapping by 10%. This is
important to create HRSC image mosaics with sufﬁcient overlap as
well as with similar illumination and viewing conditions. With the
latest orbit change to an 88:25 resonance, the time between 2
adjacent ground tracks results in major differences with respect
to local time, altitude, and atmospheric conditions. Hence, the
requirement to control the offset between adjacent sub-pericenter
points was relaxed to save fuel and Mars Express became a “free-
ﬂying” orbiter.

Further parameters of major relevance to HRSC operations are the
available data downlink capacity (Fig. 10c) and power resour-
ces. The Mars Express data transfer rate is directly related to the
Earth–Mars distance and varies between 22.8 and 228.5 kbit/s for
a ground station with a 35 m antenna dish. The number of HRSC
images and respective data volumes reﬂect the changes in
downlink capacity. During solar conjunction, the data rate falls
well below 1 kbit/s; for this reason, normal science operations
have had to be interrupted for about a month ﬁve times during the
mission. Restrictions in power are especially related to periods
with long-lasting eclipses.

Science pointing maneuvers are restricted to not more than
two science pointing requests within one orbit, and a science
pointing should not exceed 90 min; the duration for nadir pointing
is restricted to 68 min. Mars Express was pointed in nadir direc-
tion during most of the Mars surface observations and a correction
of the yaw angle is used to compensate for the rotation of Mars. An
offset angle in the cross-track (roll angle) or along-track direction
(pitch angle) can be applied to optimize targeting and image
overlap which, however, shall not exceed an angle of 20° with
respect to the nadir orientation. The second type of pointing fre-
quently used by HRSC is an inertial pointing, i.e. the axis along the
line-of-sight (which is co-aligned with the z-axis of the spacecraft)
is kept ﬁxed with respect to the celestial reference frame. Addi-
tionally, HRSC requests an inertial pointing for the x-axis of the
spacecraft to ensure that the CCD lines or the edge of the SRC
frame are oriented perpendicular to the relative velocity vector.
Thus, a nadir-like inertial pointing can be realized for a short
period which allows mapping observations at offset angles > 20°
while as imaging of the Martian moons. Inertial pointing is also
used for observations of the Martian limb, from high altitudes,
of stars and star ﬁelds or of targets of opportunity (e.g. comets,
asteroids). For very speciﬁc observations, a slew by the spacecraft
can be applied with a maximum slew rate of 0.15°/s. HRSC nor-
mally requires swells around the spacecraft axis oriented in parallel
to the CCD lines. Examples are imaging of Phobos at distances
smaller than 200 km to partially compensate for motion smear,
scanning of star ﬁelds with the HRSC pushbroom device for cali-
bration purposes, so called spot pointing for tracking a surface area
to investigate its scattering properties, and the “broom calibration”
observations from high altitudes (see Section 2.2 and Fig. 11),
when the line-of-sight is slewed within the orbit plane to scan the
Marten surface from limb to limb with all nine HRSC lines and at
nearly identical viewing and illumination conditions within min-
utes. These broom calibration observations have been performed

| Table 3 |
|------------------|------------------|
| HRSC achievements from launch until 26 March 2014. | |
| Mars Express launch | 02 June 2003 |
| Mars Express orbit insertion | 25 December 2003 |
| Mars Express end of nominal mission | 30 November 2005 |
| Current Mars Express mission extension | # 4 (until end 2014) |
| Summary of HRSC achievements until 1st HRSC image | 09 January 2004, orbit # 8 |
| In Mars orbit: | 26 March 2014, orbit # 12999 |
| HRSC engaged (successfully) in sequences | 3896 orbits |
| number of HRSC imaging sequences | 4427 |
| raw data volume (compressed) | 273.3 GByte |
| Level 1 data volume | 2,056.3 GByte |
| During cruise: | |
| number of HRSC imaging sequences | 24 |
| targets | stars, Earth, Moon, Mars, functional tests |
| raw data volume (compressed) | 1.4 GByte |
| Level 1 data volume | 4 GByte |
| Mars Mapping coverage, percent of Mars surface:
  < 100 m/pixel | 97.0% |
  < 60 m/pixel | 96.5% |
  < 50 m/pixel | 96.0% |
  < 40 m/pixel | 94.8% |
  < 30 m/pixel | 87.7% |
  < 20 m/pixel | 68.8% |
| Martian moons observations: | |
| Phobos | 257 |
| Deimos | 85 |
| including: | |
| Transits for Phobos: | 3x Deimos, 2x Jupiter, 1x Saturn, 1x Earth-
  - Moon 4 x Phobos passing Pleiades star field |
| Transits for Deimos: | 1x Saturn, 3x Phobos |
| Phobos shadow on Mars | 10 |
| Deimos penumbra search | 2 |
| Search for dust/moonlets/rings | 5 |
| Misc. Observations: | |
| limb observations | 243 |
| high-altitude, cloud search, others | 228 |
| “exotic” | 22 |

* With image data received on Earth.
* Based on nadir channel, not taking into account data quality, e.g., visibility, cloud coverage, data gaps, etc.
* Vesta, attempts for comet observations, aurora search, spot observations.

preferring daylight and the radar instrument preferring nighttime
conditions while UV, thermal, and plasma measurements require
both. As can be seen in Fig. 10c, the solar elevation at pericenter
drifted periodically from daytime to nighttime conditions with cor-
responding HRSC activity. With the periapsis in the night, HRSC
imaging is mainly restricted to observations of the limb, from high
altitude, or of the Martian moons. Since 2010, the daytime periods
became rather short and the solar elevation never exceeded 20°. In
fact, the nominal orbit was changed several times throughout the
mission mainly by lowering or increasing the apoapsis altitude to
optimize the illumination conditions at periapsis. Early orbit changes
were performed to improve nighttime conditions while later ones
were performed to reverse the trend towards permanent darkness at
pericenter (Fig. 10d). Orbit inclination remained rather constant
within 86.5 – 86.9°. The ﬁrst orbit change maneuver occurred in May
2004 and reduced the apocenter from 11,560 km to 10,100 km alti-
itude and the orbital period from 7.57 h to 6.72 h (Pischel and
Zeghers, 2009). All subsequent changes had a smaller impact on the
orbit. In July 2014, Mars Express needed 6.99 h to complete one
revolution around Mars. After reaching the nominal orbit, the peri-
center altitude has varied between 262 km up to 389 km through the
mission (Fig. 10e). This corresponds to HRSC ground pixel resolutions
at periapsis of 10.5 m/pixel up to 15.6 m/pixel, respectively.
since 2013 in order to further refine the radiometric calibration of the HRSC instrument.

An HRSC imaging sequence can consist of only one or up to nine channels, and optionally several SRC images in parallel. The instrument was engaged in nearly 3900 orbits until March 26, 2014 and more than 4400 imaging sequences have been recorded and downloaded (see Table 3). Nearly 95% of the Martian surface has been covered at ground pixel size of \( r \approx 40 \text{ m/pixel} \) and about 69% at \( r \approx 20 \text{ m/pixel} \) with the nadir channel and at lower resolutions in color. The maps of Fig. 12 show the highest available image resolution for each location of the surface. With the above described observational constraints, images at highest resolution are found preferentially (but not exclusively) at low latitudes and near the poles. Such maps are used not only for assessment of image quality, in particular with respect to stereo analysis, but also to define priorities for further acquisition.

The above stated coverage numbers and maps take into account multiple coverage and overlaps but do not consider image quality with respect to mapping, photogrammetric processing and geologic interpretation, as discussed below. The most important reason for loss of image quality is given by the atmospheric viewing conditions, when clouds or haze mask the surface. A good example is the summer period 2007 (MY 28), when a global dust storm impinged on HRSC surface mapping. Data gaps caused by downlink problems are of minor significance. The evolution in coverage over time is also shown in Fig. 12, where periods of major progress and of slow progress are evident and can be related to illumination conditions or downlink capacity. Note that cumulative coverage becomes flatter in more recent mission phases. This is also due to the fact that new images overlap with existing coverage more and more frequently, which reduces the net rates of increment.

Fig. 10. Mars Express orbit characteristics and evolution compared with major properties of HRSC images for mapping: (a) latitude drift of the subspacecraft and the subsolar points at pericenter passage compared with latitude and local time of HRSC image centers; (b) solar longitude (red line) compared with the HRSC image data compression ratio (dots); (c) solar elevation angle at pericenter (red shading indicates when HRSC could perform daytime imaging of the surface) and data transfer rate to a 35 m ground station antenna depending on Earth–Mars distance compared with the HRSC raw image data volume; (d) apocenter altitude, semimajor axis and inclination of the Mars Express orbit; (e) altitude above the Martian surface at periapsis (red line) compared with the ground sampling distance of HRSC images at image center. The vertical shaded bars represent Martian seasons (northern spring: bright, northern winter: dark). Mars Years after Clancy et al. (2000) are indicated at top of graph. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
2. Phobos and Deimos observations

The elliptic orbit of Mars Express reaches well beyond the orbit of the satellite Phobos. Hence, MEX is presently the only active Mars orbiter that is able to study the “far side” of Phobos in its locked rotation. The orbits of Phobos and Deimos are near-equatorial and near-circular with average distances from the center of Mars of 9376 km and 23,458 km and orbital periods of 7.65 h and 30.30 h, respectively. Mars Express approaches Phobos at distances well below 1500 km every five and a half months (Witasse, 2014) or about every 550 orbits (Fig. 13). Due to the similarity in orbital periods, a number of encounters in consecutive orbits occur during these periods. The relative flyby velocities vary between 2.0 and 4.5 km/s. Since 2008, small phasing maneuvers have been performed several times to reach flyby distances well below 100 km. The closest approach to Deimos was in orbit 9253 at a distance of 9,582 km. Approaches at about 10,000 km occur approximately every 300 days. The relative approach velocities are by a factor of 2 smaller than those for Phobos.

Imaging of Phobos and Deimos is typically planned when the distance to the spacecraft is equal to or less than 5500 km (resolution 50.6 m/pixel) and 14,000 km (resolution 128.8 m/pixel), respectively, and the observation and illumination geometry is favorable. Observations at phase angles greater than 100° are barely performed. Normally, the optical axis is pointed towards the center of Phobos, while the HRSC line arrays and the SRC sample dimension are set perpendicular to the velocity vector of Phobos relative to the spacecraft. In order to verify the spacecraft attitude, the observations are typically shifted in time slightly away from the point of closest approach to have an observable star (i.e. magnitude < 9) in the SRC FOV. There are three main different imaging modes of the HRSC/SRC camera that have been in use: The nadir channel together with SRC, the five stereo channels together with SRC, and the four color channels together with SRC. A detailed overview of the Phobos and Deimos observations until December 2012 (end of the 3rd mission extension) is given in Witasse (2014). Since then HRSC has performed 58 new observations of Phobos and 17 of Deimos. A summary of the Martian moon observations is given in Table 3. Recently, Phobos was captured together with the Earth and Moon and Jupiter. Also, both Martian moons were captured together with Saturn (Fig. 14). Such observations provided very good control of the spacecraft attitude and data for position determinations of Phobos and Deimos (see Section 5).

3. Global topographic mapping

3.1. Stereo analysis and DTM generation from single-strip observations

HRSC DTMs and orthoimages from data of single orbital passes have been continuously produced during the course of the mission since 2007 (Gwinner et al., 2008, 2010a), and have been archived at PSA and PDS. The global DTM of the MOLA experiment (Smith et al., 2001; NASA, 2003) serves as geodetic reference for these data products (see below). Product generation on a single-strip basis is strongly supported by the along-track multi-stereo imaging principle of HRSC. For deriving accurate 3D results from the data, a comprehensive set of techniques for image preprocessing, photogrammetric adjustment and geo-referencing, surface reconstruction, rectification and map-projection, and quality control is applied.

3.1.1. Image matching

By automatic image matching (Heipke, 1997), the coordinates of corresponding points in (multiple) stereo images are determined for two purposes: as tie-point coordinates for the adjustment of the image orientation parameters (Schmidt et al., 2008a), and for dense matching, i.e. to measure a dense set of image parallaxes for surface reconstruction (Gwinner et al., 2009). In both cases, large point sets have to be derived by automatic procedures. The radiometrically corrected HRSC images together with the nominal orientation data are the starting point. In addition, the MOLA DTM (NASA, 2003) is used for pre-rectifying the stereo images. Pre-rectification enhances the quality of image matching results by compensating for scale differences caused by the elliptical orbit, by height variation (as far as is represented in the MOLA DTM), and for the non-square pixel footprints caused by the interplay of field of view, ground speed of the spacecraft, and integration time. The matching employs a pyramidal approach to account for larger parallaxes associated with imprecise initial values of the exterior orientation. Low pass filtering, including a
Fig. 12. HRSC global image coverage up to orbit 12999, March 26, 2014. Colors indicate highest available ground pixel size for the HRSC nadir channel (top; mean 18.3 m; < 54 m for 99% of the covered area) and the HRSC red channel (bottom; mean 89.5 m; < 248 m for 99% of the covered area). Bottom left: Histograms representing smallest ground pixel size of all nadir and red channel images in the coverage maps. Bottom right: cumulative nadir image coverage history at different spatial resolutions. (For interpretation of the references to color in these figure legends, the reader is referred to the web version of this article.)
locally adaptive variant (Gwinner et al., 2009), is used to increase
the number of matched points.

The search process uses a regular grid of candidate points in
one of the images (typically the nadir image). This is a natural
approach for surface reconstruction, where the aim is a complete
coverage without gaps by a dense set of points. For the adjustment
of the image orientation parameters, usually a much smaller but
well distributed set of points is sought; often feature-based
matching techniques using interest operators are applied. In the
case of HRSC data, however, a grid-based search has also proven to
be advantageous for tie-point matching. One reason is the need to
support a high temporal sampling rate, in order to fully capture
the relevant characteristics of the orientation data (e.g. oscilla-
tions, see Section 2). Secondly, a more accurate adjustment of the
resulting point cloud to the MOLA DTM is possible when a point
grid is used: Interest operators preferentially generate points at
edges, which often coincide with morphological discontinuities.
However, because of the lower resolution of the MOLA dataset,
these locations are not well suited for extracting reference heights
from MOLA which are used for bundle adjustment (see description
further on in this section), as they often show significant height
differences between MOLA and the resulting 3D points from HRSC.
For the same reason, pre-rectification using the MOLA DTM often
shows poor results close to topographic ridges, scarps, etc. (see
Fig. 25, Section 4.1). In the case of dense matching, where point
coverage is also intended for these areas, a second pre-rectification
and matching step involving an initial HRSC-derived DTM is
therefore included (Gwinner et al., 2009).

Based on approximate image coordinates obtained from cross-
correlation, multi-image least squares matching, which can reach
subpixel accuracy, is carried out in which, in the case of tie-point
matching, all points of all overlapping images are matched
simultaneously following the approach of Krupnik and Schenk
(1997). Pairwise least squares matching (Wewel, 1996) is applied
for dense matching. In both cases, an error function based on grey
value differences between transformed local image patches is
minimized by estimating the parameters of an affine transform
between the patches.

3.1.2. Photogrammetric adjustment – single-strip case

The approach for photogrammetric adjustment of the image
orientation parameters for HRSC is based on a central perspective
model adapted for line sensors (Hofmann et al., 1982). Adjusted
orientation data represent an optimum reconstruction of the
imaging geometry and enable consistent 3D modeling. Orientation
data consist of three coordinates for the perspective center, i.e. the
spacecraft/camera position in the Mars-fixed coordinate system,
and three angular pointing components that define the rotation
from Mars-fixed coordinates to the camera coordinate system.
These six components vary with time during the HRSC imaging
sequence, as the images are acquired during continuous spacecraft
motion, with a different acquisition time for each set of up to nine
images. Therefore, the exterior orientation has to be modeled as a function of time along the spacecraft trajectory.

The approach to photogrammetric adjustment for the production of HRSC single-strip Level-4 data products combines two techniques for improving the exterior orientation data of the up to nine HRSC images acquired in a single image strip, within a systematic workflow. The first technique is a combined bundle adjustment (BA, see Ebner et al., 2004; Spiegel, 2007b), a method for reconstructing the imaging geometry that uses all tie-points simultaneously in a least-squares adjustment, together with MOLA heights. The second is a sequential photogrammetric adjustment technique (SPA, Gwinner et al., 2010a) capable of including very large sets of tie-points as well as the entire MOLA DTM subset covered by the HRSC strip.

In earth-oriented aerial or space-borne photogrammetry, an adequate number of ground control points are commonly used for tying the determined 3D coordinates to a regional or global reference system. If ground control points are not available, DTMs can be used to obtain an absolute reference (Strunz, 1993). For Mars, the MOLA DTM has been recommended as the global reference dataset by the International Astronomical Union (IAU; Seidelmann et al., 2005) and is used as reference in the bundle adjustment for the HRSC images.

The functional model of BA consists of four different types of observation equations, one each for image co-ordinates, observed orientation parameters, orbit bias and drift parameters that can account for systematic effects in the orientation parameters, and the MOLA reference DTM information. The four types of observation equations are described in Spiegel (2007a) and Bostelmann et al. (2011). HRSC bundle adjustment is carried out in two steps (Spiegel, 2007b). In the first step, only the three angles of the exterior orientation are refined, without bias and drift parameters, and without reference to MOLA. In the second part, bias and drift are included, and the height of the 3D points is constrained to lie on the MOLA surface with a certain weight. In this way, the absolute position of the image strip is adjusted iteratively. Both steps include blunder detection by robust estimation techniques. In the first step, blunders in the tie points are detected iteratively by analyzing the residuals of the adjustment. In the second step, the difference between the MOLA surface and the HRSC points is used to eliminate outliers.

The second method employed for adjustment is the sequential photogrammetric adjustment (SPA, described in more detail in Gwinner et al. (2010a)), SPA includes a comprehensive set of procedures that use bundle adjustment results as input, or start from the nominal orientation data. The optimization of the orientation parameters consists of an iterative application of four subsequent main steps: (1) minimize 3D intersection error for each object point by iteratively determining time-dependent corrections for the three orientation angles: roll, pitch, yaw. (2) Determine mean lateral and vertical offsets to MOLA and apply them as offset corrections for the three components of orbit position. (3) Analyze along-track vertical deviations to MOLA as a function of time and update correction values for the pitch angle. (4) Check for systematic across-track model tilts compared to MOLA and update offset to the correction table for the roll angle. Iterations are stopped when the multi-ray intersection error changes by less than 1%, lateral shifts are smaller than 25 m, the vertical offset to MOLA are smaller than 2 m, and the final offset correction for the roll angle is smaller than the IFOV of HRSC (0.0023°).

BA is the theoretically more accurate approach, modeling all systematic and random effects in a single and therefore consistent mathematical model, which can be easily extended to multiple orbits. A significant advantage of SPA, on the other hand, is related to its ability to process very large point sets quickly, while still obtaining highly accurate results. Thus, a very high spatial and temporal sampling density can be achieved. Typically, several 100,000 3D points per image strip can be used, or between 500 and 1000 3D points for each second of image acquisition, each derived from up to five stereo images.

Both BA and SPA, as well as the subsequent steps for surface reconstruction and generation of orthoimages (see below), include substantial numerical and manual (i.e., visual) checking procedures that are applied systematically for validation purposes and selection of alternative processing options. The quality of the nominal and adjusted exterior orientation data is compared by analyzing the resulting 3D point sets. Here, the quality criteria taken into account include the forward ray intersection error (in terms of mean value and spatial variation), the deviation of height values from MOLA and respective spatial variations, as well as the completeness of point coverage over the entire HRSC image strip. The mean intersection error summarizes the precision of all object points and is therefore a useful measure for the overall internal consistency of the data (Gwinner et al., 2009). Results obtained for many datasets have demonstrated that this parameter shows a relative improvement in almost all cases for both bundle adjustment and SPA. Typically, the error improves by a factor of approximately 1.5 compared to the nominal orientation data, and quite often by a factor of 2–4; higher improvements occur occasionally (Gwinner et al., 2009, 2010a; Bostelmann and Heipke, 2011, 2014). For more than 2500 HRSC stereo datasets successfully adjusted using BA, a failure rate of less than 5%, e.g. due to data gaps, extremely low texture due to dust storms, etc., has occurred. The progress of SPA processing corresponds to the progress of the systematic Level-4 production (see Section 3.5).
Maps representing the spatial distribution and intersection errors of dense 3D points as used for DTM generation and based on nominal and adjusted orientation data are examined by numerical tests and also by visual inspection. Such maps for the cases of orbits 2091 and 8500 (Fig. 15) show considerable improvement after bundle adjustment, despite the relatively low density of matched points in the northern part of orbit 2091 (in the southern half of the image strip, 85.6% of the DTM cells are filled by valid 3D points, compared to only 65.7% in the northern half). The mean intersection errors are reduced accordingly. Orbit 8500 is affected by high frequency spacecraft oscillations as described in Section 2.5 and visible in the initial error map. These are successfully modeled and compensated by the adjusted orientation data.

Since SPA works with dense point sets and the entire MOLA grid, it is also applied as an efficient validation tool for the bundle adjustment results. Based on a systematic procedure for testing, using for example error maps similar to the one in Fig. 15, BA results are validated for use as final orientation data for the strip, are further improved by SPA adjustment if suggested by the quality figures obtained after application of SPA, or eventually replaced by a SPA solution based on the nominal orientation where the application of BA was less successful.

3.1.3. Generation of single-track DTMs

DTM generation aims at a detailed continuous surface representation from dense sets of 3D points obtained by image matching and forward ray intersection. Both the derivation of precise 3D points and the interpolation technique to create the surface representation were shown to require an integration of adaptive processing components and efficient internal mechanisms for quality control in order to achieve optimal results (Heipke et al., 2007; Gwinner et al., 2009, 2010a). This requirement is caused by variations in point density and precision that are linked, among others, to the variability of the Mars surface, as well as the variability of the Mars Express orbit and its effects on resolution, the season and local time of data acquisition, related variation of illumination and atmospheric conditions, and, ultimately, compression rate (see Fig. 10). The key elements of the process (e.g. adaptive filtering of image data, multi-resolution approach in matching and DTM generation, photogrammetric analysis of ray combinations and intersection quality) have been described in detail elsewhere (Gwinner et al., 2009); they are applied in a systematic way to produce Level-4 data products from all HRSC stereo image strips, based on improved orientation data from single-strip adjustment. Again, standardized quality check procedures involving the criteria mentioned in the previous section are regularly applied.

The quality characteristics of the Level-4 single-strip products were assessed in detail using the first approximately 700 stereo datasets of the mission (until orbit number 2217; Gwinner et al., 2010a). This study showed that about 40% of the DTMs have a mean intersection error of better than 10 m, and about 95% better than 25 m, with an average value of 12.9 m. This corresponds to 0.67 of a nadir pixel for the respective data sets, or 30% of the mean stereo image resolution. After adjustment to MOLA, the mean standard deviation of height values as compared to MOLA tracks was reported as 34.5 m with a range of 16.2–58.7 m (39.7 m and 16.2–81.2 m for the same HRSC DTMs but including interpolated gap areas; Gwinner et al., 2010a). The residual deviation of height values between the two datasets can be ascribed to the internal precision of the datasets rather than to the uncertainty of registration to global coordinates (see Section 3.4 for the latter aspect). Specifically, after successful co-registration, the height deviation is dominated by the measurement uncertainty of both data sources as well as systematic differences in the representation of topographic detail. In particular, the distance between single MOLA shots is 300 m along-track, and the nominal spot diameter is 168 m, whereas most HRSC Level-4 DTM grids have grid spacing < 100 m (see Gwinner et al. (2010a), for a more detailed discussion).

3.2. Stereo analysis of image blocks and generation of multi-orbit DTMs

The generation of DTMs and image mosaics from a number of adjacent and overlapping HRSC images (i.e., an image block) opens up additional processing options for product generation, compared to the single-strip case. Accordingly, multi-orbit data processing involves additional methods introduced in the following
sections, as well as a number of processing steps used for single-strip processing. Fig. 16 provides an overview of the entire workflow for single-strip and multi-orbit processing, their most important links, and common procedures for the two product types.

### 3.2.1. Strategies for tie point matching and bundle block adjustment

Efficiently extracting tie-points in large image blocks requires a suitable processing strategy. It is not reasonable to deal with all image strips of the entire block simultaneously because only neighboring image strips overlap. Therefore, the image block is broken down into sub-blocks (i.e., a smaller block consisting of a subset of all images forming the block) which additionally allows for parallel processing. For each sub-block, a reference image is defined which is matched against all other overlapping images. This strategy is depicted on the basis of three overlapping image strips in Fig. 17, where one image strip may be covered by 3–5 HRSC stereo images (see also Schmidt (2008b)).

Three sub-blocks are formed in the combinations 1 and 2, 2 and 3 and 3 separately. Under the assumption that for each image strip five stereo images have been acquired (using the nadir channel and the forward and backward viewing S1, S2, P1 and P2 channels; see Fig. 2), for sub-block 1 the nadir channel of the first strip is matched against all other nine images (S1, S2, P1 and P2 of strip 1 and all five panchromatic images of strip 2). Sub-block 2 (strips 2 and 3) is handled in the same way. The third sub-block in this example simply consists of strip 3. At this point merely the remaining area which is not covered by strip 2 is processed, and matching is carried out between the different images of strip 3. An advantage of this approach in particular with strips of inhomogeneous ground resolution is that for each sub-block a separate average pre-rectification resolution can be defined. For each matching step a certain number of tie points is sought.

In the subsequent bundle block adjustment the results of the sub-blocks are processed simultaneously. The process uses the exterior orientation from the single-strip adjustment as initial values. These usually already exhibit a high relative accuracy, including corrections for possible spacecraft oscillations. They also serve to reduce the search space for tie-point matching, which generally results in more robust matching results. Iterative blunder detection is performed initially for all strips independently, as described above, and subsequently also for the overlapping areas. Again, the blunders are detected firstly in ray intersections only, and secondly with reference to the MOLA DTM (Spiegel, 2007b; Dumke et al., 2008). For evaluating the bundle block adjustment results, the mean intersection error is assessed only for points lying in an overlapping area. This reveals the improvement of the bundle adjustment of blocks more clearly than if all points of a sub-block were used.

Fig. 18 illustrates the step-wise reduction of the relative position error for individual points located in the overlapping areas of a small image block, starting from the case of nominal orientation data, where point displacements on the order of 5–10 pixels are common. After single-strip adjustment, residual displacements are still apparent; by contrast, they are reduced to the pixel size and smaller after bundle block adjustment. The magnitude of these offsets is a critical parameter for the generation of multi-orbit DTMs and high-resolution image mosaics and is therefore considered in more detail using a representative test data set (Section 3.4).

### 3.2.2. Generation of multi-orbit DTMs

Integration of 3D points from multiple orbits into a single DTM product offers obvious advantages for the further use of the data products. This has been demonstrated, using a specifically adapted
technique for DTM generation, for the four final landing site candidates of the Mars Science Laboratory (MSL) mission (Gwinner et al., 2010b). Moreover, DTM quality can be improved in several respects by multi-orbit point integration, as compared to the case of a single simple mosaic produced from single-orbit DTMs (see Fig. 19). Firstly, DTM gaps caused by image gaps, shadows, or clouds that may appear in one of the single-strip DTMs may be closed by the superimposition of points deriving from an overlapping image strip. If gaps in the point coverage achieved for an image strip (or parts thereof) are numerous and gaps are larger than a few pixels, no single-strip Level-4 DTM is produced for this strip. Therefore, multi-orbit DTMs may achieve a net increase in surface coverage compared to a mosaic of the corresponding set of single-strip DTMs. Secondly, mosaics produced from single-strip DTMs are likely to show artefacts at strip edges, related to weakly constrained interpolation close to strip borders. Finally, the joint interpolation approach avoids the masking of higher resolution datasets by lower resolution datasets without the need for implementing a fixed strip placement sequence, which would in turn require the acceptance of trade-offs concerning other parameters relevant to quality.

In order to exploit such advantages, surface reconstruction has to meet certain additional requirements in the case of multi-orbit DTMs. First of all, we assume that, as a rule, multi-orbit DTMs should provide the same or higher quality than the single-strip Level-4 DTMs. 3D points are therefore produced using the full set of stereo analysis techniques and parameter estimates applied for single-strip Level-4 processing. When co-registration of the involved image strips at the scale of their ground resolution is required, bundle-block adjusted orientation data should be applied in this process. As a minimum requirement, the adjustment has to ensure geometric consistency of overlapping point sets at the scale and height resolution of the DTM, i.e. the points should not show systematic position offsets in excess of the grid spacing of the DTM (for horizontal position) and, likewise, of its vertical precision (for vertical position).

DTM interpolation in the multi-orbit case also needs to allow for variations in density and precision of the points derived from the different orbits, since these can be noticeable for HRSC data (see Gwinner et al. (2010a)). For the single-strip DTM, a variable definition of the DTM grid spacing has been introduced to allow for an approximately constant number of 3D points that contribute to each grid height. In the case of multi-orbit DTMs, a fixed grid spacing has to be applied for the point datasets from all strips, and spatial variation of point density and quality is addressed by varying (i.e., scaling) the radius of grid interpolation accordingly. Grid spacing is chosen as the smallest value that would be selected for grid spacing among all involved datasets in the single-strip case. By using this setting, we ensure that the spatial resolution is equal to or higher than for the corresponding single-strip DTMs in each location.

For the cases of both single-strip and multi-orbit DTMs, the integration of 3D points into a regular grid of DTM heights involves distance weighted averaging within a local interpolation radius (Gwinner et al., 2009). Interpolation is controlled by constraints on local point density and distribution to reduce numerical effects due to superimposition of point sets arranged in similar but not exactly congruent matching grids (according to differences in scale, projection, and footprint position of the images used for matching). Fig. 20 shows the example of a multi-orbit DTM produced according to the methodology described above, and further discussed in Section 3.4. The DTM is composed of 3D points from 23 orbits and covers a subset of the MC-11 quadrangle of Mars.

### 3.3. Ortho-rectification and image mosaics

Orthoimages provide the metric properties of a map and complement the continuous description of surface topography represented in the DTM. HRSC orthoimages are obtained by rectification of the images based on the high-resolution HRSC DTMs (Gwinner et al., 2010a). For this reason, HRSC orthoimages are available exclusively for areas covered by HRSC DTMs. The rectification process takes into account the perspective properties of the images as dictated by the imaging principle of the sensor, its distortion parameters, the spacecraft position and camera pointing, as well as the global shape and local surface morphology of the target. Moreover, it makes use of the improved orientation data used for DTM processing and therefore the orthoimages of all
HRSC channels are effectively co-registered relative to MOLA by the same process. The horizontal resolution of the orthoimages (Table 6) is selected according to the best ground resolution of the respective dataset.

The linear metrics of the radiometric calibration (Section 2) are not affected by the processing steps leading to HRSC orthoimages. However, a linear contrast stretch is applied for each image channel independently during the generation of Level-4 single-strip image products in order to make best use of the 8 bit dynamic range of the data products. Since no additional contrast or color adjustment is applied in this case, mosaicking of single-strip HRSC Level-4 images will not immediately lead to a radiometrically homogeneous image product concerning shading pattern and local atmospheric features. The three images represent successive processing results.

imperative, however, considering that the radiometric complexity of HRSC images is significant. Due to variable acquisition seasons and times of day, and corresponding changes of solar illumination and atmospheric conditions, significant brightness differences are present even if the images are scaled according to calibrated radiance values (see Fig. 21, top). The figure shows a sub-area of the MC-11 quadrangle of Mars and includes a variety of typical study areas for Mars geomorphology, such as the high-albedo region of eastern Meridiani Planum, the low-albedo regions and dark deposits inside Aram Chaos and different craters, as well as chaotic terrains, channel systems and smooth plains.

Typically, different types of further analysis of such images impose different requirements on their radiometric preprocessing. For the single strip HRSC images, grey values can always be converted to calibrated radiances by applying scaling factors and offsets provided together with each image. Where further analysis depends on radiometrically calibrated grey values, the single-strip images should be used.

On the other hand, a display optimized for visual interpretation should mitigate larger brightness differences related to the conditions of image acquisition which may limit the visual consistency of image mosaics. The most important uses of HRSC image mosaics are assumed to consist in supporting the morphological analysis of HRSC DTMs, the use as a geometric reference dataset complementing the DTM, and support of context studies involving other instruments. Because these usually require images at best possible resolution, the applied methods should also be applicable at the scale of the full nadir resolution.

The methods for contrast and brightness adjustment applied in the production of image mosaics include both basic approaches for physics-based brightness normalization (e.g., Walter et al., 2015)
and contrast adjustment based on local statistics and external radiometric standards.

In the absence of a systematically applicable correction for atmospheric effects which would bring the HRSC image strips into mutual visual consistency, an alternative to an internal physical approach is to apply an adjustment to achieve consistency with an external standard and, thus, also between strips. The Mars Global Surveyor Thermal Emission Spectrometer (TES) provided a global albedo map (Christensen, 2001) at an interpolated surface resolution of 7.5 km/pixel, which can serve as such a standard. A continuously varying multiplicative factor is applied to the reflectance value of each HRSC pixel in such a way that the local mean reflectance conforms to the local mean of the external standard (Michael et al., 2015). The range of ‘local’ is chosen to be several times smaller than the HRSC strip width. The complete sequence of image processing steps for generation of brightness-adjusted mosaics starts from the single-strip orthoimages containing calibrated reflectance values and includes, in addition to the application of the external standard, Lambert normalization, optimization of the image placement sequence according to image quality (primarily spatial resolution), and contrast adjustment on individual images to compensate for the histogram flattening effect caused by increased efficiency of atmospheric scattering. As a result, we obtain an image which conforms to the external standard at large scales in terms of average brightness, but retains all the high resolution contrast features of the original HRSC image. When placed into a mosaic, the images are highly consistent with their neighbors (see Fig. 21).

### 3.4. Geometric accuracy of multi-orbit data products

The DTM presented in Fig. 20 can be considered as a representative test case for the generation of multi-orbit DTMs from HRSC stereo coverage, since we used all stereo datasets available for an extensive area (2300 × 650 km side length), covering acquisition times ranging between May 2004 and January 2013, and also the typical range of HRSC stereo images concerning ground resolution. The average image resolutions of the up to 5 stereo images of each image strip in the dataset range from 21.0 m to 55.0 m, with a mean of 38.4 m. For comparison, the respective values for the more than 700 stereo datasets used for single-strip DTM production considered in Gwinner et al. (2010a) range from 12.0 m to 96.2 m, with a mean of 42.6 m. The average resolution of the nadir channel is 17.6 m (compared to 20.3 m for the more than 700 datasets).

Two versions of the DTM were produced to assess the relevant geometric properties of the following two product types: one version is based on single-strip adjusted orientation data, as used for single-strip Level-4 processing (see Section 3.1; in the following called “SSA version”). This is the approach previously applied e.g. for producing regional DTMs for the 4 final MSL candidate landing sites (Gwinner et al., 2010b; see also Section 5). The second version is based on bundle block adjustment using between 500 and 4500 tie-points from each of the 53 overlapping areas (“BBA version”). Table 4 presents relevant quality figures for the data products obtained for these two versions.

The mean 3D intersection error does not show any significant differences between the two cases (± 8.9 m vs. ± 8.8 m). This is an encouraging result because it confirms that the already high and well-controlled internal precision of the single-strip 3D model is preserved throughout the integrated bundle block adjustment process. Comparison of the deviations from MOLA profile heights (± 36.6 m and ± 37.9 m) leads to the same conclusion.

Furthermore, we are interested in assessing the geometric consistency of the individual strips forming the block with respect to each other, before and after block adjustment. This can be done by producing single-strip DTMs and orthoimages for both sets of adjusted orientation data and by comparing the residual 3D displacements observed for individual points within the strip overlaps, analogous to Fig. 18. Fig. 22 presents color-coded maps of the horizontal components dX, dY, and the height component dZ of these residual displacements, determined automatically by matching of orthoimages. The three maps in the upper part of the figure represent the residual displacements in all overlap areas of the image block for the SSA version; the three maps in the lower part represent the same maps for the BBA version.

Inspection of the displacement maps shows that they are fairly uniform within each overlap, so that we may use the root mean square value (RMS) of the mean strip-to-strip displacement components to characterize the overall geometric consistency of the block. These RMS values are listed in Table 4 and they are smaller than the mean stereo pixel size for all three components in the BBA case and also for height in the SSA case. A more convenient measure for the geometric consistency of the block, in terms of uncertainty of position for each strip, could be derived from the individual offsets of the strips relative to an external reference. Conversely, the observed mean strip-to-strip displacements represent mutual offsets (i.e., coordinate differences) between adjacent strips and their variance \( \sigma^2 \) is given by the sum of variances related to the unknown position errors of the strips. Assuming that, statistically, both overlapping strips contribute equally to the variance of the displacements, we can use \( \sqrt{\sigma^2} \) as a 1σ-estimate for the mean relative offset (i.e., average position error) per strip relative to its neighbors.

The mean relative strip offsets are also reported in Table 4. Note that a sub-pixel scale value relative to the mean stereo image resolution (38.4 m) is indicated for the 2D (i.e., horizontal) and 3D offsets of the BBA version. Considering absolute numbers, including the mean nadir channel resolution of 17.6 m, the estimated average 2D offset of about 19 m means that co-registration is accurate, on average, to about one pixel for the nadir images, which allows the production of panchromatic orthoimage mosaics with the highest available resolution. Note that the absolute numbers also reflect the participation of low resolution datasets in

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**Table 4**

<table>
<thead>
<tr>
<th>Quality parameter</th>
<th>Single-strip adjustment (SSA)</th>
<th>Block adjustment (BBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean intersection error (for all points in multi-orbit DTM) [m]</td>
<td>8.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Height stddev with MOLA (excluding gap interpolation areas) [m]</td>
<td>36.6</td>
<td>37.9</td>
</tr>
<tr>
<td>RMS of mean strip-to-strip point displacements</td>
<td>90.5 / 65.4 / 9.3 m</td>
<td>18.2 / 20.1 / 8.6 m</td>
</tr>
<tr>
<td>dX / dY / dZ</td>
<td>2.36 / 1.70 / 0.24 pixels</td>
<td>0.47 / 0.52 / 0.22 pixels</td>
</tr>
<tr>
<td>Mean relative strip offsets 1D</td>
<td>64.0 / 46.2 / 6.6 m</td>
<td>12.9 / 14.2 / 6.1 m</td>
</tr>
<tr>
<td>dX / dY / dZ</td>
<td>1.67 / 120 / 0.17 pixels</td>
<td>0.34 / 0.37 / 0.16 pixels</td>
</tr>
<tr>
<td>Mean relative strip offsets 2D / 3D</td>
<td>78.5 / 79.2 m</td>
<td>19.2 / 20.1 m</td>
</tr>
<tr>
<td>dXY / dXYZ</td>
<td>2.05 / 2.06 pixels</td>
<td>0.50 / 0.52 pixels</td>
</tr>
</tbody>
</table>

\( a \) Fraction of the mean stereo pixel size (38.4 m).
the highest possible HRSC ground resolution of close to 10 m.

This holds even for overlapping strips with a residual height offsets between the DTM grid heights and MOLA showing a standard deviation of 1.9 m across all datasets (Gwinner et al., 2010a). The height offset value reported in Table 4, 6.6 m for the SSA version, is higher, which may be expected because it does not directly represent the registration to the common height reference (MOLA). We also note that the matching-based analysis includes several additional error sources, compared to a simple difference of DTM heights. Check points are matched automatically in two strips, independently adjusted to MOLA, and HRSC height values for the corresponding locations in two different DTMs are extracted by bilinear sampling. Nevertheless, co-registration to a common height reference with a residual offset of only a few meters can be confirmed using this approach. Almost the same residual mean height offset value, 6.1 m, is obtained for the BBA version. Thus, with vertical strip-to-strip offsets very similar to those after block adjustment, and when compared to previous results for the adjustment to MOLA, this test suggests that, for the height component, the quality of co-registration of overlapping HRSC strips can be considered already very good after single-strip adjustment.

On the contrary, significant differences between the SSA and BBA versions can be observed for the lateral accuracy of co-registration. Obtaining independent control information is problematic in this case since the grid resolution of the MOLA DTM does not allow for identification of check point coordinates at the scale of the HRSC data products. As a proxy value, the uncertainty of the co-registration process applied for single-strip processing was used, which led to a value of about half the HRSC DTM grid spacing for both line and sample, or about 60 m (1σ) on average (Gwinner et al., 2010a). Following the same rationale as for the height component, the relative strip offsets measured for the test block (64 m across-track and 46 m along-track, Table 4) provide support to these earlier estimates for the absolute position accuracy of the single-strip adjusted HRSC Level-4 products. In this case, however, bundle block adjustment is clearly shown to result in a significant improvement compared to single-strip adjustment, with residual offsets of little more than 10 m. Moreover, our matching-based estimate of the horizontal offsets can be expected to be more accurate than for the height component, because the latter, in addition, includes sampling of the two DTMs.

Finally, we note that the horizontal strip offsets even in the single-strip case amount to a fraction of the MOLA grid size and are on the order of the estimated lateral position uncertainty of individual MOLA profiles (about 100 m; Neumann et al., 2003). As the number of MOLA profiles crossing a single HRSC image is usually not large, strip-to-strip offsets on this order can be expected. Block adjusted HRSC stereo models, as we have demonstrated here, provide significantly higher internal position accuracy (small strip-to-strip offsets) and large blocks that may typically include about 100 HRSC image strips are covered by a large number of MOLA profiles. It is therefore conceivable that the absolute position accuracy (relative to global coordinates) of block adjusted HRSC DTMs and orthoimages will also turn out to be higher than that of individual MOLA profiles.

3.5. Status of global topography mapping and the new HRSC multi-orbit data products

At the time of writing, more than 1300 single-strip Level-4 datasets have been completed, covering about 40% of the surface of Mars (Fig. 23), and about 50% of all available stereo datasets have already been processed. The respective production process is well established and has been validated in detail (see Gwinner et
al., 2010a, and references therein). As mentioned above, not all datasets of the nominal stereo coverage are suitable for production of high-resolution DTMs in practice. Among the unsuitable cases, the vast majority (about two thirds) are affected by low image contrast, usually related to high atmospheric optical depth. Cloud coverage is responsible for about one third of the failures to derive DTMs. A number of datasets are affected by image gaps due to data transmission losses. However, data gaps are rarely so predominant that they completely obstruct the generation of a DTM (accounting for only a few percent of all unsuccessful cases). Areas with unsuitable stereo-coverage are identified and considered for re-acquisition of stereo data during the further course of the mission.

Ongoing investigations are focusing on the evaluation of multi-orbit DTMs and image mosaics, as in the above described representative example, and on the analysis of available image coverage at global scale. Of particular interest is the recent completion of a first full quadrangle (MC-11-E, Eastern Oxia Palus) for the global mapping of Mars by HRSC multi-orbit data products, based on the complete HRSC mission data record. This project adopts the MC-30 global mapping scheme consisting of 30 quadrangles (cf. Batson, 1990, Fig. 7), where each quadrangle is subdivided in two to limit HRSC data volumes. The multi-orbit DTM product, together with block-adjusted and radiometrically adjusted panchromatic and color image mosaics (Fig. 24) represents a new type of regular HRSC data products, referred to as “Level-5” products. MC-11-E is located at the equator and covers an E–W extent of about 1330 km (at the equator) and a N–S extent of about 1780 km. The area includes parts of Arabia Terra, Meridiani Planum and Chryse Planitia and the data products are based on 89 individual HRSC image strips. It also includes two of the four final ESA ExoMars 2018 landing site candidates.

Table 5 provides an overview of currently existing results of multi-orbit DTM processing, all of which were generated using grid spacing of 50 m and with quality parameters (mean intersection error and deviation from MOLA heights) that agree with the average values obtained for single-strip Level-4 DTMs (also reported in Table 5). Currently, such multi-orbit data products cover a total surface area of $2.9 \times 10^6$ km$^2$, which corresponds to 2% of the surface of Mars. Note that the “MC-11-E (Subset)” listed in the Table 5 refers to the dataset used for assessment of geometric quality as reported in Section 3.4 and contains 23 of the 89 datasets of MC-11-E.

The proposed set of main product specifications for the systematic production of multi-orbit DTMs and orthoimage mosaics is presented in Table 6, together with the respective specifications of the single-strip data products. The reference bodies for height and map projection are chosen to be identical to those of the single-strip case. In contrast, selection of the map projection follows a global mapping format. According to its mathematical compactness, common use, and data volume considerations, Equidistant Cylindrical projection is applied (Polar Stereographic projection for high latitudes). In contrast to the single-strip case, the spatial resolution for image mosaics is not made dependent on the ground resolution of the original images. Instead, a constant resolution of 12.5 m/pixel (panchromatic mosaic) and 50 m/pixel (color mosaic) appears feasible for the regional orthoimage mosaics, considering the achievable quality of co-registration and available image coverage, although further analysis is required with respect to higher latitudes. As reported in Section 3.3, different sub-types of image mosaics could be adopted. For the basis version, the TES-based brightness standard is applied.

The HRSC multi-orbit data products generated by the HRSC team are archived by PDS and PSA, and are classified as a new data product level (HRSC Level-5 data products). Table 7 provides an overview of all map-projected HRSC data products available from PDS and PSA and their main geometric and radiometric characteristics. In order to ensure geometric consistency, the map-projected HRSC Level-4 data products already available in the archives will be successively reprocessed using the new orientation data obtained by block adjustment as soon as these become available. Table 7 also lists typical applications for the different data products. Note that the single-strip products will remain essential for certain types of further analysis, in particular for those depending on calibrated image intensities.

4. Applications of DTMs and orthoimages

4.1. Co-registration and visualization of multiple data sources

The MOLA dataset serves as the global geodetic reference dataset for Mars (Seidelmann et al., 2005). Other mission data are referenced to MOLA through a combined adjustment, as for HRSC (see Section 3), or through any other suitable fitting technique, depending on the required level of accuracy. In general, correspondence with a gridded reference dataset can be established automatically via identical points determined by image matching, or, for the case of DTM datasets, by matching surface patches (i.e.,
Fig. 24. First completed quadrangle of the HRSC Level-5 multi-orbit DTM (color-coded and shaded representation) and of the panchromatic and color orthoimage mosaics, produced from 89 HRSC strips. Map sheet representation with annotations. Mars Quadrangle MC-11-E (Oxia Palus, East), E–W extent about 1330 km (at the equator), N–S extent about 1780 km, resolution 12.5 m (panchromatic mosaic) and 50 m (DTM, color mosaic), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Using laser altimeter data, DTM matching with height profiles (e.g., Lin et al., 2010) is also applied (Gläser et al., 2013). DTM matching provides the advantage that it can correlate stereo models with DTMs derived from other sources. It is also nominally independent of the typical causes of brightness variability between optical images that is not related to surface properties, i.e., illumination, atmospheric conditions, sensor spectral characteristics, etc. Image matching, on the other hand, can provide very high accuracy and can be used also for non-stereo image datasets.

Due to their difference in resolution, and gaps between MOLA profiles of several km at the equator, some of the high-resolution datasets that currently exist cannot be precisely co-registered to the global MOLA reference system directly, even if they provide stereo capabilities such as HiRISE (compare, e.g., procedures adopted in Golombek, 2012a). For the non-stereo data sets (e.g., CRISM, THEMIS, and most images of CTX, HiRISE, and MOC), a fundamental problem consists in correlating monoscopic images to a reference dataset represented by an elevation model. In both cases, HRSC data products referenced to MOLA as described in Section 3 can play a unique role as an intermediary geometric reference dataset bridging between MOLA and higher resolution datasets as well as non-stereo data. Moreover, for lower resolution image datasets (about 50 m up to a few kilometers of ground pixel size), HRSC orthoimages are likely to provide an improved basis for determining accurate tie-point coordinates as compared to using the MOLA dataset directly (e.g., in the form of shaded relief maps).

Co-registration on a pixel-by-pixel basis can be achieved by ortho-rectification of datasets using a common DTM. Here, the ground pixel size and off-nadir viewing angles related to the image are critical factors controlling the influence of DTM resolution and accuracy on the accuracy of the rectification result. If their orientation data can be adjusted to HRSC, other image data at or near the HRSC image scale (e.g., CRISM, CTX) can be ortho-rectified using the HRSC DTM. The quality improvements resulting from using a more detailed DTM for ortho-rectification and visualization, e.g., HRSC vs. MOLA DTMs, can be clearly demonstrated for the example of HRSC color images because their visualization, e.g., HRSC vs. MOLA DTMs, can be clearly demonstrated. Height errors lead to obvious distortions of straight morphological elements, which are clearly seen in the perspective view of Fig. 25. Moreover, color seams at selected strongly curved relief elements are a clear indication of DTM errors at those relief elements because the color images are acquired under slightly different off-nadir viewing angles.

As mentioned before, the quality of orthorectification essentially depends on the orientation parameters of the image data to be rectified. This includes the interior orientation of the sensor, i.e., its geometric calibration. It is therefore worth noting that the photogrammetric adjustment processes can be essential also for registering different observations so they can be compared at full resolution to assess subtle differences such as temporal change, spectral features, and photometric effects. In this respect, for example the imaging spectrometer OMEGA of Mars Express can benefit from HRSC-based improvements of spacecraft orientation data. Even though the ground resolution of OMEGA is far below that of HRSC, the extent of the improvements is relevant and may exceed the scale of one or more OMEGA pixels. Studies of atmospheric features using OMEGA data have used HRSC 3D data for co-registration and data reduction (Scholten et al., 2010; Määttänen et al., 2010; see also Section 4.8).

Often, co-registration is only a first step in a joint analysis of multiple surface data or for multi-temporal analysis (see examples in Sections 4.5–4.8). For an initial assessment of relationships between different data, or for the verification of results (e.g., mapping results), 3D visualization techniques are used frequently. Merging of HRSC image and topography data with various other data sets for joint visualization has been applied in multiple studies, e.g., OMEGA or CRISM for mineralogical applications, and MOC, CTX and HiRISE for the analysis of small scale morphology (see example of Fig. 26). The application of advanced 3D visualization techniques also allows the implementation of specific more elaborate functionalities, e.g., for visualization-based modeling purposes such as interactive retro-deformation of faults (Westerheiger et al., 2012) or analysis of rock layering (Section 4.4).

### 4.2. Topographic maps and base maps

As unique “follow-up” products of stereo-photogrammetric mapping systems, digital maps, base maps and GIS layers are among the most important higher level data products of HRSC, where fundamental cartographic characteristics are directly related to the production of the photogrammetric Level-4 data products. The raster DTM itself is genuinely created according to a specific map projection and geodetic reference system. By the process of orthorectification the images acquired from the spacecraft are also transformed to the reference system of the DTM or to any other appropriate cartographic reference system. Thus, both DTM and orthoimage share the geometric properties of a properly geo-referenced map and are “GIS ready” data products in this sense – to the extent that the particular GIS or cartography software is prepared to properly handle the data formats, metadata and geometric reference systems commonly used for Mars data.

For the purpose of generating print-ready digital maps from Mars data, the cartography software Planetary Image Mapper (PIMap; Gehrke et al., 2006a) has been developed. In addition to

<table>
<thead>
<tr>
<th>Site name</th>
<th>Latitude range</th>
<th>Lon. range</th>
<th>Elevation range [m]</th>
<th>Grid spacing [m]</th>
<th>Area coverage [km²]</th>
<th>Mean 3D intersection Error [m]</th>
<th>Deviation with MOLA heights (Std.dev.) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gale Crater</strong></td>
<td>3.2°S</td>
<td>135.0°E</td>
<td>–4680</td>
<td>50</td>
<td>275 × 205</td>
<td>11.6</td>
<td>29.1</td>
</tr>
<tr>
<td><strong>Mawrth Vallis</strong></td>
<td>19.8°N</td>
<td>139.3°E</td>
<td>1460</td>
<td>50</td>
<td>530 × 650</td>
<td>9.7</td>
<td>26.8</td>
</tr>
<tr>
<td><strong>Holden and Eberswalde</strong></td>
<td>22.5°S</td>
<td>323.7°E</td>
<td>–3140</td>
<td>50</td>
<td>625 × 235</td>
<td>12.9</td>
<td>29.5</td>
</tr>
<tr>
<td><strong>MC-11-E (Subset)</strong></td>
<td>32.9°S</td>
<td>328.1°E</td>
<td>1880</td>
<td>50</td>
<td>2300 × 650</td>
<td>8.9</td>
<td>36.6</td>
</tr>
<tr>
<td><strong>MC-11-E</strong></td>
<td>0°N</td>
<td>375.5°E</td>
<td>–4540</td>
<td>50</td>
<td>3460 × 1330</td>
<td>8.5</td>
<td>34.9</td>
</tr>
<tr>
<td><strong>PDS single-strip DTMs</strong></td>
<td>global</td>
<td>global</td>
<td>–</td>
<td>50–175</td>
<td>–</td>
<td>12.9 (avg.)</td>
<td>34.5 (avg.)</td>
</tr>
</tbody>
</table>

Table 5: Main characteristics of the HRSC multi-orbit DTMs for the four final MSL landing site candidates (Gwinner et al., 2010b; see also Section 5), the first quadrant of the new HRSC Level-5 multi-orbit data products for Mars (MC-11-E), and the subset of quadrangle MC-11-E used for discussion in Section 3.4. Respective average quality numbers for HRSC single-stripe DTMs (Gwinner et al., 2010a) are also listed and agree with those of the multi-orbit DTMs.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Single-strip DTM</th>
<th>Multi-orbit DTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production status</td>
<td>40% completed</td>
<td>First prototype completed (MC-11-E)</td>
</tr>
<tr>
<td>Spheroid DTM</td>
<td></td>
<td>Spheroid DTM</td>
</tr>
<tr>
<td>Panchromatic (Nadir), Red, Green, Blue and Near-Infrared Channel Orthoimage</td>
<td>16 bit (Gray), depending on quality of image</td>
<td>Spheroid r = 3396 km and GMM3-derived equipotential surface (Areoid DTM)</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>50–100 m</td>
<td>Spheroid r = 3396 km</td>
</tr>
<tr>
<td>Map projection</td>
<td></td>
<td>Equidistant Cylindrical (±37° latitude)</td>
</tr>
<tr>
<td>Map projection</td>
<td></td>
<td>Polar Stereographic (polar areas)</td>
</tr>
</tbody>
</table>

4.3. Quantitative geomorphology

Many studies in quantitative geomorphology are relying on basic geometric parameters such as length, width, height, area, and slope angles of specific morphologic features. For studies based on remote sensing, which is still the rule in planetary science, the precision of such measurements is of course related to the accuracy of the topographic data products used. First-order error estimates for the quantitative analysis of HRSC 3D data products can be based on the correlation between image resolution and average 3D point precision, which has been derived from a large number of stereo datasets (67 percent of the nadir resolution; Gwinner et al., 2010a), and error propagation. The average 3D point precision is derived from the intersection error (see Gwinner et al., 2010a) of all 3D points used to produce a particular DTM and describes the uncertainty of 3D position at the 1σ-level. Moreover, the measured features have to be clearly identifiable in the datasets. Here, stereo images offer a unique strength in providing terrain models as well as superimposed image data. A variety of HRSC-based studies have been exploiting such geometric properties and relationships, for example to investigate paleo-hydrological parameters (Jaumann et al., 2005; Erkeling et al., 2009) and erosion by lava flows (Williams et al., 2005) based on channel geometries, fluvial deposition processes based on the geometry of delta-like deposits (Di Achille et al., 2006; Hauber et al., 2009; Kleinhans et al., 2010), local climatic conditions due to terrain slopes and exposition (Reiss et al., 2009), tectonic deformation (Kronberg et al., 2007), or volumes of surface deposits...
More complex geomorphological studies typically involve parameters related to the spatial arrangement of morphological elements, as is the case for regional-scale hydrological studies (e.g., Marra et al., 2015).

HRSC data have been found well suited for the quantitative study of fluvial processes, because they cover wide surface areas at high resolution. These data enable studying the spatial organization and the geometry of valleys and channels at watershed scale, both in 2D and 3D (Fig. 29). The detection of valleys or channels in HRSC DTMs has followed standard techniques used to extract terrestrial drainage networks from topographic datasets. These are based on simulation of continuous flow paths taking into account the topographic slope and a threshold on the flow accumulation.

Thus it is possible to extract and quantify useful morphometric parameters at valley and channel scales (width, depth, slope, areas and volumes), and at watershed scale, e.g., the Strahler order of valley organization (Strahler, 1952), valley distribution parameters such as the exponent of Hack’s law (Penido et al., 2013), or the bifurcation and length ratios, to determine which fluvial processes were responsible for their formation.

Numerous valley networks have been studied with HRSC datasets, occurring in different geographic areas, lithology, and formed at different ages (e.g., Jaumann et al., 2005; Ansan et al., 2008; Mangold et al., 2008; Ansan and Mangold, 2013). In these studies, the automatic detection of valley networks was very efficient for an HRSC DTM with a grid spacing of <100 m.
Although the number of automatically detected valleys has been found to be about three times smaller than for manual mapping using HRSC images (Fig. 29) it was also 2 to 20 times larger than the number of valleys extracted from the MOLA DTM (Ansan et al., 2008).

In each drainage basin, valleys show a branching pattern with valley segments that can be assigned to a segment order. According to Strahler’s system, which is commonly applied to the Martian surface, valley networks studied using HRSC DTMs typically reach the fifth order (Ansan et al., 2008; Ansan and Mangold, 2013). This appears relatively low in comparison to the highest Strahler order (i.e. 7) found by Hynek et al. (2010) from a combination of MOLA and IR THEMIS data. However, for the same area, the analysis of HRSC DTMs has resulted in one Strahler order more than for MOLA (Ansan et al., 2008).

Longitudinal and transverse profiles along main valleys or channels can be used to estimate parameters related to paleohydrological dynamics such as erosion power at valley scale or volume of water and discharge in wide channels. HRSC DTMs were found to permit extraction of transverse profiles at a minimum width of about 500 m and a minimum depth of about 20 m (Jau- mann et al., 2005; Ansan et al., 2008; Mangold et al., 2008; Ansan and Mangold, 2013). For comparison, the mean width and depth of the features for detection in MOLA data was reported as about 3 km and about 100 m, respectively (Williams and Phillips, 2001). Even smaller dimensions allowing such identifications are possible for HiRISE DTMs (Kirk et al., 2008), but these do not cover areas wide enough for the study of valley networks.

Studies of sedimentary landforms have included estimates for the volume of deposited materials derived from HRSC DTMs. In the case of deltaic bodies, for example, when these volumes are compared against flow discharge in associated channels (also derived from the DTMs), a minimum formation time for these deposits can be determined assuming a given water-to-sediment ratio. This approach has been applied to various fan-shaped deposits interpreted as deltas, mainly in Xanthe Terra (Hauber et al., 2009). It appears that they may have been formed in geologically very short timescales (days to years; Kleinhans et al., 2010), although it is not possible to account for intermittency of channel runoff, which could significantly extend the total time required to form the deltas.

4.4. Structural geology

In planetary science, structural geology relies strongly on morphological features related to layering and deformation of the subsurface (e.g., Schultz et al., 2010). In addition to classical mapping approaches (e.g., Hauber and Kronberg, 2001, 2005; Fernández and Anguita, 2007), two methods that make specific use of superimposed orthoimages and DTMs have been applied with great success to HRSC data: measurements of layering geometry and mapping of displacement distribution along fault lines.

4.4.1. Layer measurement technique

Given a planar surface arbitrarily oriented in space, any three points on that surface uniquely determine its orientation. In practice, errors in the spatial coordinates of those points introduce errors in that orientation. By measuring more points on the surface, this error can be reduced, and by using multi-linear regression, the error in orientation can be estimated. In practice, a candidate planar geological contact is sampled within the nadir orthoimage and the best-fit plane through those points is calculated together with associated fitting and error statistics. The vertical deviations of the points from that plane are chosen for minimization because the user chooses the horizontal coordinates of the sample points on the flat projection of the orthoimage while the vertical coordinate is provided by the DTM. The deviations can result from the uncertainty of the elevation data, from misidentifying points within the image that do not follow an actual plane and from the surface being not truly planar. Existing software applying this approach, e.g., Orion by Pangaea Scientific (Fu et al., 2008), also provides functions for tracing the fitted plane over the image, and displaying a 3D projection of the fitted plane superimposed on the image as draped over the topographic surface (Fig. 30).

Given a set of points distributed about a planar surface in X, Y and Z coordinates, the multilinear regression equation is \( Z = a + bX + cY \). Here, \( a, b \) and \( c \) are the partial regression coefficients. The strike is found from the equation \( S = \arctan(b/c) \) + \( \pi/2 \) and the dip from \( D = \arctan(1/\sqrt{b^2 + c^2}) \). The confidence limits for the strike and dip values can be derived from the standard error of the partial regression coefficients, \( \sigma_D \) and \( \sigma_S \), using standard statistical methods. The standard errors of the strike and dip, \( \sigma_S \) and \( \sigma_D \), are then found by error propagation (Crow et al., 1960, p. 69; Baird, 1962, p. 48 ff), giving:

\[ \sigma_D^2 = \frac{c}{b^2 + c^2} \sigma_Y^2 + \frac{b}{b^2 + c^2} \sigma_X^2 \]

\[ \sigma_S^2 = \left( \frac{c}{b^2 + c^2} \right)^2 \sigma_Y^2 + \left( \frac{b}{b^2 + c^2} \right)^2 \sigma_X^2 \]
\[ \sigma_0^2 = \frac{b^2}{b^2 + c^2 + 1} \sqrt{b^2 + c^2} \sigma_b^2 + \frac{c^2}{b^2 + c^2 + 1} \sqrt{b^2 + c^2} \sigma_c^2. \]

The most comprehensive study involving layer measurements on HRSC data was presented by Fueten et al. (2008) and involves HRSC orbit 2116 within west Candor Chasma. Layers were measured on several mounds of interior layered deposits (ILD) using a DTM with a spacing of 50 m. The average sample spacing was 50 m or more, often 100–150 m. In the study 205 separate layers were measured, with end-to-end trace lengths ranging from about 600 m to 11 km, with an average trace length of 2.6 km. The average maximum deviation for all layers was 2.9 m, less than 1.5% of the plane’s trace length, illustrating both the high accuracy of the DTM and the planarity of the geological data. Because identification of the proper dip direction is very important for shallow dipping data, particular attention throughout the measuring process was paid not only to the maximum deviation, but also to the dip error. As a result, for all planes with dips greater than 2°, the dip error is less than the dip of the plane, with an average dip error for the entire data set being 1.7°. HRSC data have also been used to measure fault geometry in a number of additional studies of ILD (e.g., Fueten et al., 2011, 2014).

4.4.2. Displacement mapping along fault traces

Geometric fault properties can provide insights into the mechanical and temporal evolution of fault systems (Cowie and Scholz, 1992; Cartwright et al., 1995) and the past and future potential for seismic energy release (Wells and Coppersmith, 1994).
In planetary science, where a lack of seismometers is unfortunately the rule rather than the exception, the analysis of faults and, more rarely, folds with remote-sensing data typically provides the only direct observational evidence to constrain the tectonic history of a planet (Schultz et al., 2010). DTM and orthoimages from HRSC can be used to obtain information on the displacement distribution along fault traces. This also enables the determination of the maximum displacement and the displacement-length ratio.

Faults are mapped on the basis of HRSC DTMs (Fig. 31a) and corresponding orthoimages. Fault segments are mapped individually (Fig. 31b). Fault length is digitized along the fault line, and multiple topographic cross-sections with an orientation normal to the fault trend are drawn with a spacing of about 1 km. Fault throw (a proxy for true displacement assuming steeply dipping normal fault planes) is then measured for each cross-section (Fig. 31c). The resulting fault displacement profiles for individual fault segments are analyzed with respect to fault linkage, applying the linkage criterion of Soliva and Benedicto (2004). If segments are linked, an aggregate or cumulative fault displacement profile is constructed (Fig. 31d). It is then straightforward to identify the maximum displacement along the fault (Hauber et al., 2014).

4.5. Color imaging and compositional mapping

The five spectral bands of HRSC offer near-global coverage of the surface of Mars at different wavelengths and high resolution and therefore are used to support global and regional studies both in terms of visual interpretation and quantified multispectral information. In particular, in joint use with hyperspectral datasets, HRSC color data are used to improve the compositional mapping of the surface. Datasets such as OMEGA and CRISM have been used for mapping different minerals at the surface of Mars, including igneous minerals like pyroxene and olivine, secondary minerals such as various sulfates, clay minerals, and oxides (e.g. Bibring et al., 2006; Poulet et al., 2007; Murchie et al., 2009), as well as ices (e.g. Langevin et al., 2007). While the HRSC multispectral dataset alone cannot directly constrain the mineralogy, it has been used to...
Fig. 29. Drainage density of valley networks in Terra Cimmeria, eastward of the Hellas basin, as measured in various datasets. a) Mosaic of HRSC images (orbit 0228 and 0241), 30 m/pixel; b) manual mapping of valley networks overlaid on HRSC images; c) semi-automatic mapping of valley networks overlaid on HRSC DTM; d) semi-automatic mapping of valley networks overlaid on MOLA DTM. The number of detected valleys increases with spatial resolution. In this area, the mean drainage density is 0.06 km$^{-1}$ for MOLA, 0.23 km$^{-1}$ for HRSC DTM and 0.27 km$^{-1}$ for HRSC images, respectively (Ansan et al., 2008).

Fig. 30. Dipping layer in ILD in West Candor Chasma, as measured by Fueten et al. (2008). HRSC data from orbit 2116. Measurement based on 21 points spaced over a trace length of 6930 m with a Maximum Deviation of 4.9 m, Goodness of Fit of 99.97%, and strike and dip errors of $\pm 7.1^\circ$ and $\pm 1.0^\circ$. The light colored plane is the calculated plane.
refine the compositional mapping based on mineral maps from hyperspectral datasets at a higher resolution and/or with a larger coverage. As mineralological identification is mainly performed in the near infrared (NIR) spectral range with OMEGA and CRISM, and as HRSC observes Mars mainly in the visible range, comparing both datasets requires that compositionally different surface materials display spectral differences both in the NIR and the visible. In addition, McCord et al. (2007) emphasize the significance of precise co-registration for quantified spectral analysis, i.e. the significance of ortho-rectifying the color channels, in this particular case for spectral classification and unmixing for a number of characteristic surface units.

A comprehensive study in the region of Mawrth Vallis has identified extensive deposits rich in clay minerals, where two main species have been identified, one richer in Al, the other richer in Fe/Mg, using distinctive absorption bands in the NIR domain (Poulet et al., 2005; Loizeau et al., 2007; Bishop et al., 2008; McKeown et al., 2009). When comparing mineral maps with HRSC RGB images, a strong correlation shows Al-clays in bluer tones and Fe/Mg-clays in redder tones (see example Fig. 32, and Loizeau et al., 2010). Comparing laboratory spectra of these clays shows, for example, indeed a stronger absorption in the short visible wavelengths for the Fe-clay mineral nontronite. HRSC has been very helpful for mapping the entire clay-rich unit at high resolution because OMEGA offers a ground resolution of a few hundreds of meters at best, while CRISM offers only a partial coverage of the region at about 20 m. When combined with height information from the HRSC DTM, the mineralogical mapping
obtained this way, and lithologic mapping more in general, can provide valuable insights into the regional stratigraphy (e.g., Le Deit et al., 2008; Bishop, 2013).

Joint analysis of data from different instruments can also make use of data fusion techniques. McGuire et al. (2014) for example have applied a “dodging and burning” technique similar to the approach of Fahnestock and Schowengerdt (1983) for adding a high pass-filtered version of a HRSC image mosaic to a low pass-filtered version of an OMEGA 1.08 μm-albedo mosaic (Ody et al., 2012). This allows displaying the high-frequency detail information retained from HRSC together with the low-frequency contextual OMEGA albedo variations at higher spatial resolution (475 m/pixel in this example, while the original OMEGA mosaic has only 1500 m/pixel).

4.6. Multi-angle observations: atmospheric optical depth and surface photometry

Multi-angular observations from HRSC (see Fig. 2, which also displays off-nadir viewing angles) have proven useful for documenting the optical depth of the Martian atmosphere (Hoekzema et al., 2010) and the photometric properties of the Martian surface, i.e. for mapping the variation of the soil and bedrock physical properties of Mars (Jehl et al., 2008; Pinet et al., 2014).

![Image 33](url)

**Fig. 33.** Left: Subset of orbit 0471 image of HRSC showing the northern wall of Valles Marineris. The East–West distance is 141 km. Right: the black dots with error margins give the optical depths that were retrieved with the stereo method as a function of altitude, across the wall of Valles Marineris. The measurements show a clear relation that can be well fitted with an exponential curve. The fit is indicated with stars, and implies a scale-height of optical depth of 14.0 ± 1.1 km, which agrees with estimates from global circulation models [e.g., www8].

4.6.1. The optical depth of the Martian atmosphere

The atmosphere of Mars contains a haze of reddish airborne dust and other aerosols. In the visible, this haze, which commonly has an optical depth of 0.3–10, has a strong influence on the colors, contrast and spatial resolution of images. Correcting for the effects of this haze becomes possible to some extent if the optical depth is known (e.g., Stenzel et al., 2008). During the mission, two methods for retrieving optical depths have been validated and calibrated: the ‘stereo method’ and the ‘shadow method’. Before the Mars Express mission, no validated methods existed because required measurements from the surface of Mars were missing and only became available after the landing of the two Mars Exploration Rovers (MER; Crisp et al., 2003) in early 2004.

The **stereo method** estimates the optical depth from differences in contrast between the stereo images of HRSC. Images taken by the forward-looking and backward-looking channels show less contrast on the surface than nadir images, because the forward and backward views have a longer path-length through the atmosphere and thus experience stronger atmospheric extinction. These contrast differences are a measure of the optical depth. Hoekzema et al. (2010) show that the stereo method can yield usable estimates of the optical depth when a set of HRSC stereo images displays very high contrasts (Fig. 33). The method has high potential, because it can be automated and because it can map the optical depth using continuous multi-angular observations from HRSC. However, Hoekzema et al. (2010) also show that the use of this method is limited by high demands on the intensity calibration of the images, and for many datasets the accuracy of results was limited. Availability of the DTM is vital for the stereo method since it allows for sub-pixel accurate co-registration of the multi-view images by orthorectification, and by this minimizes a potential additional error source of the method.

A second method for determining optical depth, the **shadow method**, is applied to single images and is based on image contrasts due to shadows. Using shadow areas as small as a few tens of pixels, the shadow method can be used to study small scale variations of the optical depth (e.g., due to clouds). The most important drawback of the method is that many images of Mars do not show usable shadows if the sun is more than some 30° above the horizon. The shadow method was first used by Markiewicz et al. (2005). It estimates the optical depth from the brightness difference between sunlit regions and shadowed ones. This difference is large under a clear sky but decreases with increasing optical depth of the overlying atmosphere. Petrova et al. (2012) demonstrated that it is sometimes possible to model the conversion between brightness difference and optical depth very...
accurately, based on additional data on the albedo and the bidirectional reflection properties of the surface, the local surface topography, the distribution of diffuse illumination from the sky, and sky visibility for each location. However, for most images of Mars such inputs are not all available.

Therefore we usually use a simplified version of the shadow method (Hoekzema et al., 2011), based on a fit between optical depth and the difference in brightness between sunlit and shadowed regions. It was optimized by comparing optical depth measurements by the MER rovers with shadow-method retrievals from HRSC images of regions around their exploration sites. Usually, retrievals from panchromatic HRSC images have errors of less than $\pm 15\%$ ($\pm 8–10\%$ in favorable cases). The relative errors between various retrievals from the same image are usually smaller than this and in practice one can observe spatial variations in the optical depth if these are larger than about 5%.

Shadow-method results in combination with HRSC DTM heights offer unique data for studying optical depth as a function of surface altitude. By now we have successfully used the shadow method to analyze HRSC images from more than 150 orbits. This growing data-base of optical depths with corresponding DTM heights is unprecedented and offers new ways to study airborne dust and ice in the atmosphere of Mars. For example, we observed that during the afternoon the scale-height of optical depth commonly is very similar to the scale-height of pressure. In contrast, it often appears much smaller during the early morning. This indicates that aerosols are well mixed into the air during the daytime but not in the early morning, when they might be concentrated.
near the surface. Fig. 34 provides optical depth vs. altitude plots illustrating the two cases, as well as further explanation.

4.6.2. Surface photometry

The set of five overlapping images can be used to extract photometric information within the limits of the range of photometric angles sampled (Neukum and Jaumann, 2004; McCord et al., 2007). Furthermore, since they can be accurately co-registered, HRSC observations from several overlapping strips acquired at different times during the mission can be combined in order to cover as well as possible the phase angle domain (Pinet et al., 2005, 2006). Thus, a greater phase angle coverage can be achieved by combining carefully chosen HRSC observations acquired at different times under varying illumination geometries and low atmospheric opacity conditions. Pinet et al. (2006) used 10 overlapping HRSC strips with varied geometric conditions to derive integrated phase functions over a wide range of phase angles and classify the photometric diversity for Gusev Crater and the south flank of Apollinaris Patera (Fig. 35).

The strips have been obtained within 2 years, with 2 orbits (0024 and 0072) at low phase angle (g < 50°; f = 30°), 2 orbits (0637 and 0648) at high phase angle (g > 60°; associated with dawn illumination conditions, 1–80°) and 6 additional orbits (0987, 1879, 2249, 2271, 2685, 2729) with varied geometric conditions. The data of all panchromatic HRSC channels of these orbits are orthorectified at 1.6 km/pixel resolution using the HRSC DTM, which allows the co-registration of the five panchromatic images from each strip and all images from the different orbits, more in general, with an accuracy significantly higher than the pixel size (Gwinner et al., 2010a). The scale reduction also minimizes compression effects. With very oblique illumination conditions, observational limitations are the shadows caused by the local relief and decreased S/N ratio. Taking advantage of the extended phase domain ranging up to 95°, associated with a diversity of illumination conditions, the Hapke inversion procedure of Cord et al. (2003), employing a double Henyey–Greenstein function, could be applied successfully to model the surface photometric properties.

Based on the inversion process and a classification step (Principal Component Analysis), the photometric diversity at 675 nm, as seen from orbit, of the Martian surface properties across Gusev crater can be depicted with seven units (Fig. 35; Jehl et al., 2008). The most pronounced photometric changes are observed in three of these units associated with the low-albedo features corresponding to dark wind streaks. These units (i) have a low single scattering albedo, (ii) are the most backscattering surfaces across Gusev, (iii) have a high surface roughness, and (iv) present variable surface states as shown by the opposition parameter estimates, all being consistent with the occurrence of large grains organized in more or less closely packed layers. Clear differences are seen among these units in terms of the characteristics for the opposition effect, where at least one unit suggests the occurrence of a packed/compressed/narrow size distribution powder surface.

The opposition effect thus appears to play a significant role, suggesting that the surface-state optical properties across Gusev are strongly influenced by the porosity and packing characteristics or grain size distribution of the upper layer of the Martian soil. The mapping aspect of the investigation sheds light on the meaning of the observed photometric variations. Indeed, the Hapke modeling suggests that surface organization (surface roughness, packing state) is more important than the simple physical characterization of the intrinsic optical properties of the constitutive particles, a point supported by a recent experimental study (Souchon et al., 2011).

The HRSC-based photometric results agree with independent investigations based on thermal inertia (e.g., Christensen et al., 2005; Martínez-Alonso et al., 2005), reflectance spectroscopy (Lichtenberg et al., 2007), in situ photometric investigations by means of the Panoramic Camera instrument onboard Spirit (Johnson et al., 2006, 2008), and microscopic imaging (e.g., Herkenhoff, 2004), and support the idea of a thin layer of fine-grained dust, being stripped off in the low albedo units to reveal a dark basaltic substrate comprising coarse-grained materials.

Given the overall spatial patterns derived from the photometric analysis, the variations, at least for the western and central part of Gusev Crater, are likely in part driven by the prevailing wind regimes, considered to be oriented north-northwest/south-southeast and disturbing the very upper surface layer. This finding supports the suggestion of Johnson et al. (2006) that one should consider the local topography (i.e., a DTM) in modeling the wind patterns and regimes to address the variability and efficiency of aeolian weathering activity (Greeley et al., 2006).

Building upon this seminal study, an advanced solution separating out the atmospheric and surface photometric contributions has been recently implemented on specific regions of interest, based on CRISM observations (Camanos et al., 2013; Fernando et al., 2013). The comparison between these independent results shows that there is a robust overall consistency (Pinet et al., 2014), which opens up the possibility of more detailed studies concerning dust opacity conditions.

4.7. Multi-temporal observations and change detection

Several studies using HRSC data have addressed change detection related to active processes on Mars including aeolian, impact cratering, and polar processes. Opportunities for multi-temporal observations of variable features on Mars arise from the already near-global coverage by HRSC (Fig. 12), and an increasing number of repeated image acquisitions of the same surface areas. After more than 10 years in orbit, HRSC covered many surface areas for several times, some smaller areas more than 10 times. Surface changes can be detected using multi-temporal HRSC images or by combining HRSC observations with other imaging instruments from, e.g., MRO, MGS, and Mars Odyssey. A multi-temporal database that allows to survey the spatial and temporal availability of HRSC image data and also other Mars mission instruments has been implemented recently (Erkeling et al., 2014).

Aeolian processes are the most dynamic processes acting on the Martian surface. Recent studies revealed that current wind conditions are indeed capable of transporting not only dust but also sand and thus result in measurable dune migration rates (Kok, 2012; Yizhaq et al., 2013). With typical transport distances of up to 1–2 m for ripples on top of dune bodies in one Martian year, dune migration is unlikely to be observable with HRSC data alone and can rather be analyzed with or in combination with other instruments such as MOC or HiRISE (e.g., Bourke et al., 2008; Silvestro et al., 2010; Bridges et al., 2012; Silvestro et al., 2013). However, aeolian processes are often associated with albedo changes over broader areas, such as dust devils tracks or wind streaks, which in turn can be observed with HRSC. Also dust devils themselves are observed in a number of HRSC images, showing diameters of about 50 m and larger. Changes of wind streaks and dust devil tracks were investigated in Gusev crater (Fig. 36) using multi-temporal HRSC and THEMIS-VIS imagery (Greeley et al., 2005, 2006). Here, the streaks were observed to fade, i.e. they tend to get brighter, possibly due to the settling of dust from the atmosphere. Slope streak changes were analyzed with a multi-temporal data set consisting of HRSC, Viking Orbiter, CTX, and HiRISE imagery (Schroghofer and King, 2011). HRSC image data were also used in combination with MOC and THEMIS data to find new impact crater sites and to narrow down their formation age (Malin et al., 2006). Interannual changes of the North Polar Cap were investigated.
using Lambert albedo from multi-temporal HRSC image data (Reiss et al., 2008).

In contrast to a purely visual comparison of multi-temporal data, quantitative multi-temporal analysis essentially depends on accurate co-registration of the different datasets involved. According to the geometric characteristics presented in Section 3, multi-temporal studies using HRSC alone will typically be able to rely on co-registration accuracy of one DTM grid spacing or better, when based on single-strip adjusted data, which can be improved to attain about one image pixel or better when based on block-adjusted data.

4.8. Direct observation of dynamic processes

The imaging principle of the HRSC instrument allows the tracking of dynamic processes on Mars because the 9 image

Fig. 36. Evolution of dark wind streaks and dust devil tracks in Gusev crater (MER Spirit landing site) during three Martian years. (A) orbit 0024 (2004-01-16, Mars Year (MY) 26, Ls 334') showing in most cases dark dust devil tracks and crater-related wind streaks. (B) orbit 2271 (2005-10-20, MY 27, Ls 309') after a dust clearing event by wind gusts. (C) orbit 4165 (2007-04-03, MY 28, Ls 212') showing again in most cases dark dust devil tracks and crater-related wind streaks. See for comparison also Fig. 1 in Greeley et al. (2005).

Fig. 37. Regional dust storm with five dust devils in front of the dust storm. The dust devils and the dust storm are moving in SSW direction with a speed of approximately 20 m/s (see also Stanzel et al., 2010). Left to right: stereo2 (A), nadir (B) and stereo1 (C). HRSC image from orbit 2054. The time interval between the stereo2 and stereo1 images is about 52 s.
channels cover the same surface area at different times, resulting in time differences between the first and last imaging channels (stereo 1 and 2 or vice versa) of normally 1–2 min. Based on the set of images from one orbital pass it is therefore possible to determine, for example, the translational speed of dust devils, dust storms, and clouds.

Stanzel et al. (2006, 2008) measured the translational speed (ground speed) of 205 dust devils ranging between 1 and 59 m/s. In addition, Reiss et al. (2011) measured translational speeds of 26 dust devils ranging between 3 and 22 m/s. With typical average image resolutions (about 25 m/pixel) and maximum time intervals between the image captures (about 100 s), speeds as low as 0.3 m/s can be measured using HRSC. In some cases the dust devils were observed in front of moving regional dust storms (Stanzel et al., 2010). Measured translational speeds and directions of motion of dust devils observed in HRSC can be used to infer minimum duration times (lifetimes) of dust devils, especially if compared to additional image observations at the same day by other orbiters. For example, the comparison of dust devils observed in Syria Planum by the HRSC with image data acquired on the same day by the Mars Observer Camera – Wide Angle (MOC-WA), with a time delay of 26 min, allowed the constraint of the minimum lifetimes of dust devils (Reiss et al., 2011). This study showed that larger dust devils have much longer lifetimes than smaller dust devils on Mars as is the case on Earth.

Other dynamic phenomena that can be tracked using HRSC images include cloud motion. Using the short-wave blue (440+/− 45 nm) and green (530+/− 45 nm) bands of HRSC, for example, it is possible to determine the velocity of the East–West motion of CO₂ clouds in the Martian mesosphere (Fig. 38). These bands are located slightly off-nadir (+/− 3.3°) in the along-track direction, which in addition allows the determination of the altitude of the clouds. The clouds are not apparent from the panchromatic nadir and stereo channels. The measurement principle and an assessment of cloud morphologies and geographic distribution using a set of HRSC images acquired within one Martian year have been presented in Scholten et al. (2010).

The clouds have been confirmed to consist of CO₂ by data from the OMEGA spectrometer acquired within the same MEX orbit. The East–West velocity (or cross-track velocity, with the polar Mars Express orbit) of these clouds is derived from the time difference between the respective observations in the two bands and the apparent across-track displacement. Scholten et al. (2010) derived CO₂ cloud altitudes in the range of 66–83 km (about 1–2 km accuracy), and East–West velocities in the range of 60–93 m/s (accuracy ~10–13 m/s). A detailed study of CO₂ clouds using Mars Express data taken over nearly three Martian years, combining HRSC altitude and velocity measurements with spectral characteristics derived from OMEGA, is presented in Määttänen et al. (2010).

5. Exemplary use cases

5.1. Martian satellites: observation and mapping of Phobos and Deimos

5.1.1. Astrometric observations

SRC images obtained during Mars Express Phobos flybys and Deimos approaches were used in order to determine the center-of-figure (COF) positions of the two moons. Measurement techniques were refined over time. Oberst et al. (2006) fitted predictions of the satellites’ limbs – based on their tri-axial ellipsoid models – to limbs observed in the images (limb-fit method). In contrast, Willner et al. (2008) measured positions of known control points. Pasewaldt et al. (2012) used a refined limb-fit procedure, in which limb shapes were predicted using the satellites’ shape models. Because typically only predicted attitude data are available from ESA, the pointing is verified and improved by means of background star measurements (Willner et al. 2008, Pasewaldt et al. 2012). Since mid-2005 long-exposure background star observations are typically included in Phobos and Deimos imaging sequences.

Oberst et al. (2006) reduced 26 Phobos and 10 Deimos observations obtained from May 2004 to April 2005 with 1-sigma errors of 0.5–5.0 km for Phobos and 1.0 km for Deimos. Willner et al. (2008) published 67 Phobos observations with accuracies between 0.1 and 0.5 km that were derived from images taken between 2004 and 2007. Pasewaldt et al. (2012) produced a dataset of 136 Deimos observations for the time period from 2005 to 2011 with uncertainties ranging from 0.6 to 3.6 km. The latest set of 158 Phobos observations and a comparison of the refined limb-fit procedure and the control point method are summarized by Pasewaldt et al. (2015). Uncertainties range from 0.2 to 3.4 km.

Since early positional measurements over the satellite orbit predictions revealed large offsets of Phobos and Deimos positions by approximately 12 km and 50 km, respectively, the astrometric observations were used to update and improve the Phobos and Deimos orbit models. The new orbit models reveal a host of dynamic parameters of Mars’ satellite system, including gravity models of Phobos, Deimos and interior structure (dissipation) models for Mars. The models shed light on the origin and long-term evolution of the two moons.

5.1.2. SRC control point networks

The geodetic reference system for Phobos is typically realized by networks of control points, represented by prominent surface points (almost all small craters), for which body-fixed coordinates, i.e., latitudes, longitudes, and radii, are precisely known. The coordinates of the surface points are determined from the measurements of their line and sample coordinates in large numbers of overlapping images (“image blocks”) by iterative inversion techniques (bundle block adjustments). A byproduct of the adjustments is the corrected spacecraft navigation data for all images that are involved, useful for production of co-registered images and maps.

The control point clouds represent a critical framework for shape models. From tracking of the apparent motion of control points over time, unknown rotational parameters of the planetary body (e.g., rotational axis orientation or librational motion) may be determined. Control points are also used as reference markers for the above mentioned positional measurements of the target body against the star background.
Based on SRC images, a large control point network was derived (Willner et al., 2010). The network included a total of 665 points using 3898 measurements in 69 images with mean point accuracies of 40 m. More recently, a new control point network was derived involving 813 control points, observed in 202 SRC and Viking images (average point accuracy: 13.7 m), including new image data, not previously used for control point analysis (Oberst et al., 2014). Also, a new technique for direct tracking of Phobos librations was presented.

5.1.3. Geodetic control - HRSC block adjustments

HRSC images of 18 close flybys, covering almost the entire surface of Phobos were co-registered to the SRC control point network (Willner et al., 2014). Conjugate points were selected between the 5 HRSC images of each flyby as well as between images of different flybys. Taking advantage of near-simultaneous image acquisition, automated routines were used for the matching of images from one flyby, respectively. However, automated matching of images acquired during different flybys has been found impracticable due to differences in illumination and image resolution. Hence, tie points were collected manually in these cases. In addition to the tie point measurements, points of the SRC control point network were introduced as fixed points during the subsequent bundle block adjustment. The bundle adjustment provides a unique but self-consistent set of exterior orientation data for all included flybys. As a result, co-registration to the reference data set was achieved with an accuracy of $+/- 30$ m with respect to the SRC control point network.

5.1.4. Phobos shape and topography modeling

For the modeling, we use an approach that includes part of the procedures described in Gwinner et al. (2009) but also procedures specifically adapted to a small celestial body such as Phobos. Prior to matching, images are pre-rectified based on a spherical harmonic function model computed on the basis of the SRC control point network coordinates. This minimizes the disparities between the images and thus the likelihood of false identification of conjugate points. Automated matching is applied to the HRSC stereo, photometry, and nadir images of one flyby at a time. Again, matching between images from different flybys turned out to be impracticable for the reasons stated above. As a result, we obtained 18 jigsaw piece-like parts of the global DTM, which must be merged.

Unfortunately, the resulting DTMs vary in quality and resolution, mainly due to differences in the flyby geometries and pixel binning. Although some parts of the surface can be reconstructed with greater detail (up to about 40 m/pixel resolution) and low noise, a DTM grid spacing of 100 m has been found appropriate for the global DTM of Phobos, i.e., 2.5 times the average resolution of the photometry channel images.

5.1.5. Orthoimages and maps

The first orthoimage mosaic (20 m/pixel) of two HRSC images was based on image data from the unique Phobos-approaching orbit 0756 (Giese et al., 2005). Subsequently, a near-global orthoimage mosaic of Phobos was derived from 26 SRC orthoimages in a resolution of 16 pixel/$\circ$ (12.11 m/pixel), based on an earlier control point network and DTM (Willner et al., 2010). Three topographic image maps of Phobos were produced and combined into an atlas at a scale of 1:50,000 (Wählisch et al., 2010). Stooke (2012) compiled a new global mosaic of Phobos in a resolution of 40 pixel/$\circ$ combining selected high-quality images from Viking, Mars Global Surveyor, Mars Express, and MRO. The images were processed and reprojected to fit a Viking-based (Simonelli et al., 1993) or the above mentioned SRC-based map (Stooke, 2012). More recently, an updated global SRC orthoimage mosaic (20 m/pixel) has been developed on the basis of a new control point network and using a larger selection of 123 SRC images (Oberst et al., 2014).

The first near-global controlled mosaic derived from HRSC images (Wählisch et al., 2014; Willner et al., 2014) is based on 18 selected HRSC imaging sequences which were ortho-rectified on the basis of the Phobos control-point grid and shape model of Willner et al. (2014). A selection of 10 HRSC orthoimages was used for the final mosaic in a resolution of 16 pixel/$\circ$ and sub-mosaics were generated for the poles (Fig. 39). These mosaics form the basis for the production of a topographic atlas at 1:50,000 scale. The atlas consists of six topographic image maps: three maps show dynamic heights derived from gravity field modeling (Shi et al., 2012), the others show geometric heights derived from the DTM (Willner et al., 2014). The coordinates and dimensions of 17

Fig. 39. Synthetic perspective view of the South Pole of Phobos from HRSC-derived shape model and orthoimages. Right: perspective rendering of the image mosaic composed of 10 HRSC imaging sequences and represented in Polar Stereographic projection. Left: with color coded spheroid heights and annotations.
craters with names confirmed by the International Astronomical Union (IAU) have been re-determined.

5.2. Mars and Phobos landing sites: use of HRSC for site selection and characterization

The future of Mars Exploration will increasingly be driven by the need for in situ investigations on the Martian surface, with the ultimate goal of Mars Sample Return (MSR) (e.g., MEPAG E2E-ISAG, 2011). Eight landers and rovers have already successfully been deployed at the Martian surface, and four additional landing missions are in preparation (Fig. 40). Any landing site of a planetary lander or rover needs to be scientifically compelling and technically safe. Technical parameters that have to be considered during the landing site selection process include slope angles at different base lengths, the thermal inertia of the substrate, dust coverage, and rock abundance. Moreover, the landing site has to meet criteria such as a given latitude and/or elevation range. These constraints require the analysis of a multitude of spatially resolved data sets (e.g., Golombek et al., 2003, 2012a; Arvidson et al., 2008) that need to be geometrically co-registered to a global geodetic reference. This base reference elevation dataset is the gridded MOLA DTM (Smith et al., 2001) at −0.5 km/pixel. It uses a positive east planetocentric coordinate system referenced to the IAU/IAG 2000 frame, compatible with the inertial coordinates typically used by spacecraft navigation teams (e.g., Golombek et al., 2003, 2012a).

MOLA data are unique for their global coverage by accurate height profiles that form the best available global geodetic reference dataset for Mars, but their spatial resolution is not sufficiently high for many investigations focusing on local areas. Therefore, other datasets with higher spatial resolution are critical for examining small-scale characteristics of landing sites. For example, the identification of rocks (boulders) and rock size-frequency distributions is nowadays based on the analysis of HiRISE images (Golombek et al., 2008, 2012b) which have a typical ground sampling dimension of ~30 cm/pixel and a swath width of ~6 km (McEwen et al., 2007). Due to the extremely different spatial resolution of MOLA and HiRISE, it is not straightforward to co-register HiRISE directly to MOLA. HRSC with its intermediate resolution is an ideal “bridge” to enable common geometric registration of datasets with diverse resolutions (see also discussion in Section 4.1). This approach has been successfully applied during the landing site selection for the Mars Science Laboratory (MSL) mission (Golombek et al., 2012a, Grant, 2011). For all four final MSL candidate landing sites, regional HRSC multi-orbit DTMs (50 m/pixel; see Table 5 for information on main characteristics), each covering a surface extent of several degrees in longitude and latitude, were produced and coregistered to MOLA as part of their production process (Gwinner et al., 2010a,b). Next, CTX images (~6 m/pixel; Malin et al., 2007) were coregistered to the HRSC images, and finally HiRISE orthoimages were georeferenced to the CTX rectified image base (this process is described in detail in Golombek et al., 2012a). The DTMs covering the four candidate landing ellipses in Gale, Holden, and Eberswalde Craters and in the Mawrth Vallis region (Fig. 41) were made available to NASA and the general public via the Europlanet IDIS node “Interiors and Surfaces”, hosted by DLR [www9].

HRSC data have also been used to evaluate the landing site for ESA’s ExoMars Entry, Descent and Landing Demonstrator Module, named Schiaparelli. Schiaparelli is a technology demonstration vehicle carried by the ExoMars Trace Gas Orbiter, which will be launched in March 2016 to demonstrate the capability of European industry to perform a controlled landing on the surface of Mars. The preparation for this mission enhances Europe’s expertise and enables the testing of key technologies which could be used in subsequent missions to Mars. The landing site will be in Meridiani Planum, near the landing site of the Mars Exploration Rover, Opportunity (Golombek et al., 2003). HRSC DTMs enabled the determination of slopes at scales of about 100 m (Ori et al., 2014). In combination with other datasets such as CTX and HiRISE, HRSC images were also used to produce a geological/geomorphological map of the entire 110 × 25 km² landing ellipse.

Elsewhere, HRSC data also supported the geological characteristics of landing sites. For example, Le Deit et al. (2013) used the HRSC multi-orbit DTM and orthoimages of Gale Crater, the landing site of MSL, to analyze slopes and to count craters for absolute model age determinations. HRSC data also provided insights into the geologic diversity of fan-shaped deposits in Xanthe Terra and the Libya Montes area (Hauber et al., 2009, 2013; Erkeling et al.,...
which led to the proposal of three candidate landing sites for future missions, and acceptance of proposals to acquire MRO

data in the context of NASA’s Critical Data Products Program (Hauber and Le Deit, 2012; Erkeling et al., 2011).

Moreover, HRSC data were used for a detailed analysis of the envisaged target area for the Phobos Grunt Sample Return Mission (PhSRM) lander. In March 2010, HRSC observed Phobos during three close flybys with the nadir and stereo channels providing between 4 m/pixel and 19 m/pixel ground resolution and the two photometric channels between 9 m/pixel and 39 m/pixel. A local digital terrain model for the designated landing sites (Basilevsky and Shingareva, 2010) was computed and referenced to the control point network and global shape model by Willner et al. (2010) (Fig. 42). At the available resolution, no boulders were detected within the landing site area which could have jeopardized a safe landing. The data also enabled determining the landing site coordinates with respect to the geodetic reference frame established by Willner et al. (2010) (site 1: 217.7 °W / 15.5 °N; site 2: 212.0 °W / 21.5 °N).

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**Fig. 41.** HRSC multi-orbit DTMs of the final four candidate landing sites of the MSL rover, Curiosity. The white crosses mark the centers of the proposed landing site ellipses. On the left sides: Plan views (north is up); on the right side: perspective views. Color-coded elevations (red = high, blue = low). (a) Gale crater. The full DTM covers 275 × 205 km². The perspective view on the right is to the northeast. (b) Mawrth Vallis. The DTM covers 530 × 650 km. Perspective view on the right is to the south. (c) Candidate sites for Holden and Eberswalde craters. The DTM covers 625 × 235 km². Perspective view on the right is to the southwest. (For interpretation of the color-coded heights in this figure, the reader is referred to the web version of this article.)

**Fig. 42.** Perspective view of the expected landing site area with the two designated spots for landing (Basilevsky and Shingareva, 2010).
Due to Phobos’ irregular shape, low mass, fast spin rate, and proximity to Mars, surface acceleration and slopes can be quite different from what would be anticipated from Phobos’ self-gravitation alone. Working models of Phobos’ “dynamic environment” were produced, with grid spacing of 1° (Shi et al., 2012), based on the Phobos shape model (Willner et al., 2010, 2014) and tidal and rotational force models. For further analysis of the designated landing sites, map overlays showing the effective surface acceleration and down-slope vectors were produced (Fig. 43). It was concluded that the area chosen was situated in a rather smooth region, where steep slopes were not to be expected.

6. Summary and outlook

In this paper, in addition to providing an updated overview of the status and evolution of the experiment, we have focused on the specific capability of HRSC to provide precise topographic information by means of stereo observation and analysis. After more than 10 years of operations in orbit around Mars, the HRSC camera instrument including the SRC is fully functional without noticeable signs of degradation. Currently, 97% of the surface of Mars has been covered by panchromatic HRSC images with ground pixel size smaller than 100 m, and about 69% smaller than 20 m. Mapping the Martian surface globally at spatial resolutions of preferably < 20 m/pixel and in stereo is the major mission goal for HRSC. In addition, more than 300 observations of the Martian satellites have been accomplished.

Based on a comprehensive set of processing techniques for 3D data analysis, more than 1300 Level-4 product datasets, i.e. high-resolution DTMs with up to 50 m grid spacing and corresponding orthoimages (up to 12.5 m/pixel ground resolution), have been derived from individual HRSC strips. They currently cover about 40% of the surface of Mars. The geometric characteristics of these single-strip data products have been addressed in detail in different previous publications, in particular the precision of derived 3D points (smaller than the pixel scale, with an average value of 12.9 m) and the quality of co-registration with the MOLA dataset, and were briefly reviewed in this paper. For Phobos, a global DTM (100 m grid spacing) and different orthoimage mosaics have been produced from HRSC and SRC. These datasets are referenced to control point networks that have been updated using SRC images. We also reported on specific improvements to the geometric and radiometric calibration of the instrument that were derived from analysis of in-flight data acquired in Mars orbit.

The capability of deriving topographic data products on a single-strip basis is supported by the along-track multi-stereo principle applied by HRSC. On this basis, the position and attitude data can be determined by means of photogrammetric adjustment with sufficiently high accuracy for the purposes of a high-resolution stereo imaging device. This includes correcting for the effects of oscillations of the Mars Express spacecraft with amplitudes as small as 0.001° (i.e., close to theIFOV of HRSC), that occur under specific conditions. Such oscillations cannot be determined at the required level of precision by other means, although their existence is evidenced by spacecraft housekeeping data.

A major strength of HRSC can be seen also in the provision of the concomitant orthoimages, which are precisely co-registered with the DTM on a pixel-by-pixel basis. Orthoimages can be directly applied for map generation and 3D visualization together with the height information from the DTM, and joint analysis of both data sources supports a multitude of applications for science analysis. A number of the approaches from the fields of quantitative morphology, structural geology, compositional mapping, and atmospheric science we have addressed in this paper are benefitting from precise co-registration, not only of image and DTM data but also of multiple image datasets among each other, in particular those methods that make use of quantitative analysis techniques, multi-angular observations, or multi-temporal observations.

Since the data products are tied to the global MOLA reference system, HRSC plays a unique role as intermediary geometric reference dataset for Mars, linking MOLA to other stereo datasets, in particular stereo datasets providing higher ground resolution such as CTX and HiRISE (via image correlation or DTM matching), and to non-stereo datasets (via image correlation). No other instrument that has been flown to Mars or is planned for a future mission is supporting the task of global 3D mapping at a resolution better than 100 m/pixel. HRSC has also proven high complementarity to the primarily profile-related MOLA data by high-resolution DTM grids, in particular where MOLA is affected by wide longitudinal gaps.

At this point of the mission, continuous surface coverage by adjacent HRSC stereo datasets is getting increasingly available. Integration of 3D points from multiple orbits into a single regional DTM product offers obvious advantages for data handling and analysis. Moreover, DTM quality can be improved by multi-orbit point integration, as compared to a mosaic produced from single-orbit DTMs, with respect to reduction of gaps, avoidance of interpolation artifacts at strip borders, and improvement of resolved detail, depending on the quality of co-registration of adjacent strips. However, integration of 3D points from different HRSC image strips has to account for typical variations of point density and precision.

We presented processing results for a representative image block comprising 23 different orbits, and of corresponding geometric quality assessment using residual point displacements in strip overlap areas. The results show that the co-registration of adjacent strips can attain subpixel accuracy with respect to the mean stereo image resolution after block adjustment of the images. Point displacements in strip overlaps also provide information on the co-registration accuracy of data products based on single-strip adjustment (i.e., the single-strip Level-4 products and existing multi-orbit DTMs such as those produced for the MSL landing sites, Gwinner et al., 2010b). While close adjustment to MOLA heights on the basis of single-strip adjustment has been clearly demonstrated, previous estimates for the quality of horizontal adjustment to MOLA could only be based on residual adjustment errors for the single-strip case, since the grid resolution of the
MOLA DTM makes it difficult to measure check point coordinates with sufficient accuracy. Nevertheless, the previous estimate (approximately \(\pm 60\) m; Gwinner et al., 2010a) is found to agree well with the results derived from strip overlaps. In summary, accurate adjustment to MOLA heights can be assumed for the single-strip case, and accuracy of 2D position on the order of the DTM grid spacing (50–125 m).

Still higher accuracy of the lateral co-registration between HRSC images at the scale of the best available image resolution can be achieved by block adjustment. The current results suggest that multi-orbit DTMs with grid spacing of 50 m can be achieved at least for the equatorial quadrangles of Mars; furthermore, that the accuracy of block adjustment is sufficiently high to achieve co-registration accuracy for adjacent images at the scale of about one pixel also for the highest image resolution commonly used for generating single-strip image products (12.5 m/pixel). We also have presented a procedure for the adjustment of image brightness which is capable of producing visually consistent image mosaics from large numbers of HRSC image strips, despite of the fact that these show strong variation concerning atmospheric conditions and illumination. It involves techniques for physics-based brightness normalization, local contrast enhancement, and an external brightness standard (TES albedo).

The above-mentioned characteristics and techniques have allowed us to define a new set of HRSC data products which is based on integration of data from multiple orbits (Level-5 data products). A first corresponding mapping tile of the global MC-30 mapping scheme of Mars, covering quadrangle MC-11 (East), has been presented in this paper. Panchromatic mosaics at the best possible resolution are expected to support the most important uses of HRSC image mosaics, assumed to consist in supporting the morphological analysis of HRSC DTMs, the use as a geometric reference dataset complementing the DTM, and support of context studies involving other instruments. The completion of such multi-orbit data products also depends on successful acquisition of additional stereo data during the future course of the mission, in particular on closing existing gaps in stereo coverage and on obtaining additional stereo images for selected areas, where existing stereo observations have suffered from high atmospheric opacity, cloud cover, or unfavorable illumination conditions. Repeated observations will also further improve the basis for multi-temporal applications and change detection using HRSC.

In January 2015, MEX has entered its 5th mission extension, which lasts until the end of 2016. The actual status and health of the mission would allow a further extension. The further evolution of the MEX orbit is expected to prove beneficial for HRSC observations. As the solar elevation angle at the sub-spacecraft point at periapsis tends to rise, the periods when HRSC can observe during daylight (i.e. solar elevation > 0°) become longer (Fig. 44). At the same time, the solar elevation does not exceed values above about 36° over 4.5 years, quite ideal for imaging and good representation of texture and morphology. Very high elevation angles tend to suppress shading patterns in images, which are all important for enhancing detail in otherwise uniform dust-covered surfaces that are so common on Mars. Moreover, no orbit change maneuvers are foreseen and the trend to increasing periapsis altitude as the general control on ground pixel size does not continue (Fig. 44). Consequently, the average image resolution remains stable and the gain in surface coverage during each daylight period increases substantially as compared to the last three periods. Similarly, periods of close Phobos flybys occur as before. In summary, the period provides good opportunities to close gaps in coverage and replace images obtained under less favorable conditions.

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Appendix

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Fig. 44. Orbit evolution of Mars Express over the next years (thick vertical line marks 30 June 2014). Red line: Solar elevation at periapsis; Dashed area: Periods of daylight imaging at periapsis; Blue line: Pericenter altitude. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
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