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Multi-resolution digital terrain models and their potential for Mars landing site assessments

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ABSTRACT

One of the key issues for planetary, especially Mars surface exploration, is how to make an objective assessment of criteria for landing sites selection for future rovers, sample return missions and landers considering topographic variables such as slope, altitude and roughness as well as their physical scattering properties. For these purposes, stereo vision analysis is here proposed as the best possible solution to provide reliable topographic data. Recently, a number of successful orbital missions to Mars have taken place including the Mars Express mission with the High Resolution Stereo Camera (HRSC) as well as the Mars Reconnaissance Orbiter spacecraft equipped with two major cameras—Context Camera (CTX) and High Resolution Imaging Science Experiment (HiRISE). A stereo processing chain has been developed to generate high quality Digital Terrain Models (DTMs)—up to a maximum grid spacing of 0.7 m with HiRISE, 10 m with CTX and 25 m with HRSC along with terrain-corrected ortho rectified images. Applying this system, topographic datasets were produced over potential landing sites, which had been previously proposed based mainly on their purported geological significance. High (< 10 m) and ultra-high (< 4 m) resolution DTMs from stereo imagery were employed to confirm mainly topographical hazard free landing sites from an engineering standpoint as well as to assess the geology of the target areas. In particular, the Minimum Noise Fraction (MNF) approach has been applied to assess landing risks quantitatively based on the surface roughness of the resultant topographic products. In future, it is expected that topographic products can be integrated with other data sources such as hyperspectral imagery, radar backscattering and laser beam broadening in order to provide the physical properties for the landing site selection as well.

1. Introduction

Martian imagery and topographic data are essential elements for the scientific exploration of Mars. This includes geological analysis, geomorphological interpretation, climatic and potentially astrobiological potential assessment, and landing site selection, etc. To fulfil increasing demands from geoscientists, more Martian orbital imagery and Digital Terrain Models (DTMs) derived from various Mars exploration missions have been obtained and created over the last decade.

The first accurate systematic topographic product was based on the elevation measurements obtained by the Mars Orbiter Laser Altimeter (MOLA). MOLA was carried onboard the Mars Global Surveyor (MGS), a spacecraft that was launched on the 7th of November 1996 (Smith et al., 1999). The first comprehensive Mars topography map was produced by the time the primary mission was finished on 30th of June 2001. At the end of the mission, a gridded MOLA DTM was created at resolutions of 4, 16, 32, 64, and 128 pixels per degree (Smith et al., 2003). After subsequent investigations, Neumann et al. (2001) reported that the vertical accuracy of the MOLA heights is typically better than 1 m with respect to Mars' centre of mass, based on height differences between orbital crossings. Given its high accuracy and global coverage, the MOLA data is deemed as the most consistent Mars height reference and is usually considered as a topographic "base dataset" (Heipke et al., 2007; Kim and Muller, 2008). More details on MOLA can be found in Smith et al. (1999, 2001). It should be noted that although MOLA is an excellent height reference, the spacing between MOLA tracks can be more than 4 km at the

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equator. Therefore, users of the grid point interpolated MOLA DTMs should be cautious about the use of heights between the orbital tracks, especially near or on the equator.

The stereo image coverage of the Martian surface has dramatically increased since the successful orbital insertion of ESA's Mars Express with its onboard High Resolution Stereo Camera (HRSC) instrument on 25 December 2003. The spatial resolution of the imagery acquired by HRSC is up to 12.5 m, providing an opportunity for observing details of the Martian surface. In addition to the orbital imagery, DTMs created using the HRSC image data is an increasingly popular Martian topographic product. This nine multi-directional push-broom stereo camera system was specially designed to meet the requirements of photogrammetry and cartography for mapping the complete surface of the Mars (Albertz et al., 2005; Scholten et al., 2005). The acquired image data are therefore well suited for the automatic generation of Martian DTMs. Due to the characteristics of high resolution and the stereo imaging capability of the HRSC, the construction of Martian DTMs with grid spacing of 30–75 m is achievable (Albertz et al., 2005; Scholten et al., 2005; Gwinner et al., 2007; Heipke et al., 2007; Kim and Muller, 2009). Compared with a MOLA DTM, not only the spatial resolution of a HRSC DTM is improved significantly but its vertical height difference compared against MOLA is within 25 m rms.

In late 2006, the successful deployment of the NASA Mars Reconnaissance Orbiter (MRO) with the Context Camera (CTX) and High Resolution Imaging Science Experiment (HiRISE) instruments began to provide repeat-pass across-track stereo image pairs with spatial resolution of 6 m and 25 cm respectively (Malin et al., 2007; McEwen et al., 2007; Kirk et al., 2008). At this resolution, very detailed topographic information can be viewed and interpreted using the CTX and HiRISE images (Sanderson, 2006; Chuang et al., 2007; Braun and Manning, 2006; Chojnacki and Moersch, 2008; Dundas et al., 2008). Moreover, as the stereo image pairs are available, the acquired image data are suitable for the photogrammetric creation of very high resolution DTMs (Kirk et al., 2008). Kim and Muller (2009) showed CTX DTMs with grid spacing of 12–20 m. As for HiRISE DTM creation, it was reported that the HiRISE DTMs with resolution up to 1 m became available (Kirk et al., 2008; Kim and Muller, 2009). The topographic products provide enormous added value to scientists who need DTMs for diverse Mars explorations and applications.

Amongst the variety of proposed Mars exploration tasks, the assessment and selection of landing site for Mars lander has been playing an important topic. To achieve this, the employment of appropriate topographic data has been playing an important role. An example for the landing site selection using topographic data can be found for the ESA/UK Mars probe Beagle 2 in Bridges et al. (2003). Secondly, Golombek et al. (2003) assessed 155 potential landing sites using MOLA, image data and radar observations for Mars Exploration Rover (MER). After the two landing sites were selected for MER-A (Spirit) and MER-B (Opportunity) (i.e. Gusev Crater and Meridiani Planum respectively), the acquired remote sensing datasets were used to survey atmospheric and geological conditions (Golombek et al., 2005). Thirdly, the selection of landing site for MER was assessed using the DTMs created from the Mars Orbiter Camera Narrow-Angle (MOC-NA) images (Kirk et al., 2003). Overall it was demonstrated that the topographic data was an invaluable tool during the assessment and selection of future landing sites for Mars rovers.

Since then, as introduced above, advanced topographic products with higher spatial resolution derived from the HRSC, CTX and HiRISE instruments have become available. They are expected to deliver more accurate and detailed mapping data for landing site assessment. Moreover, as the characteristics of each imaging system is different, a "zooming-up" (multi-resolution zoom) topographic analysis over future target landing sites using DTMs at different resolutions is here proposed. To demonstrate the feasibility of this approach, three potential Mars rover landing sites were selected, including Athabasca Valles (MER former proposed landing site), Eberswalde Crater (runner-up Mars Science Laboratory (MSL) landing site) and Nili Fossae (rejected MSL landing site due to altitude considerations). Co-registered HRSC, CTX and HiRISE DTMs with MOLA covering these three sites were created and refined by co-registering them to each other. Together with 3D topographic information, the geological implications and potential applications using these topographic datasets are discussed here. This has permitted the topographic landing site assessment methods to be tested, showing one of the advantages of employing nested high resolution topography data.

It should be particularly noted that this study was performed under three presuppositions: (1) the lander/rover is assumed to possess pin-point landing ability, not considering future lander/rover's landing mechanisms and engineering characteristics, (2) the three target areas here assessed are not proposed for realistic landing site candidates in the near future. These are only chosen to demonstrate the application of the high resolution topographic products for the landing site assessments and (3) lLanding site analysis using datasets such as multi-spectral or hyper-spectral, thermal, radar and laser radiometer are excluded here. All landing site assessments are herein solely performed employing a topographic analysis.

2. Creation of Mars DTMs

The HRSC, CTX and HiRISE DTMs covering three target sites, including Athabasca Valles, Eberswalde Crater, and Nili Fossae, were processed using the methods described in Kim and Muller (2009) and Kim et al. (2012). The DTM creation method and discussion of the resultant DTM products are described below.

2.1. HRSC DTMs

The software framework used to extract HRSC DTMs in this paper was based on the Video Image Communication and Retrieval (VICAR) system. The HRSC VICAR system was developed by the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre, DLR) in association with JPL (Scholten et al., 2005; Gwinner et al., 2009, 2010) and is capable of photogrammetric processing of HRSC data. As the HRSC is a push-broom scanning instrument with nine CCD line detectors, each orbital dataset (i.e. HRSC Level-2 images) can therefore be considered as a set of multiple images covering the same area. These images are input to the HRSC VICAR processing system and the corresponding ortho-images are produced using a MOLA gridded 5 km DTM as reference. Subsequently, image matching is applied to search matching points up to nine channels upon availability. These matched image pixels are then re-projected back into the original HRSC Level-2 images, and a space intersection performed to compute the 3D coordinates of the matched points. To create the final HRSC DTM, the 3D point cloud is interpolated to generate a gridded DTM. Detailed workflow is described in Scholten et al. (2005), Albertz et al. (2005) and Gwinner et al. (2009, 2010).

Whilst VICAR software was used for the majority of the processing, a number of enhancements were carried out to create an updated HRSC DTM for this paper. Firstly, a two-stage image matching method was implemented for determining corresponding points between multi-look HRSC images. This consists of a front end image matcher based on the algorithm developed by Zitnick and Kanade (2000). This so-called ZK algorithm exploits the quasi epipolarity of the HRSC Level-2 data. High density seed