Synthetic topography from the decameter to the centimeter scale on Mars for scientific and rover operations of the ESA-Roscosmos ExoMars mission

O. Ruesch[1,2], M. Hess[3], K. Wohlfarth[3], T. Heyer[1], C. Wöhler[3], T. R. R. Bontognali[4,5], C. Orgel[2], E. Sefton-Nash[2], J.-L. Josset[4], J. L. Vago[2]

[1]Institut für Planetologie, Westfälische-Wilhelms Universität, Münster, Germany.
[2]European Space and Technology Center (ESTEC), European Space Agency (ESA), Noordwijk, The Netherlands.
[3]Image Analysis Group, Technische Universität Dortmund, Dortmund, Germany.
[4]Space Exploration Institute, Fbg de l'Hopital 68, 2002 Neuchâtel, Switzerland
[5]Dep. of Environmental Sciences, Univ. of Basel, Klingelbergstr. 27, 4056 Basel, Switzerland

Corresponding author:
Dr. Ottaviano Ruesch
Institut für Planetologie
Westfälische Wilhelms Universität Münster
Wilhelm-Klemm-Straße 10
48149 Münster
Deutschland
Email: ottaviano.ruesch@uni-muenster.de

Keywords

- Topographic modelling
- Martian surface
- Image simulation

0. Abstract

The ESA-Roscosmos ExoMars platform and rover mission will have complex interactions with the martian surface. In order to plan and perform engineering and scientific operations, the morphological characteristics of the terrain surrounding the rover need to be characterized from the decameter to the centimeter spatial scale. The smallest possible features currently identifiable are typically >0.75 m in size, corresponding to three times the ground sampling resolution of the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter (MRO). We have developed a synthetic topography with a ground sampling resolution of 0.01 m by integrating 1) a modeled topography of small-scale reliefs (*e.g.*, rocks) into 2) a 0.25 m resolution digital elevation model (DTM) built by applying stereo and shape-from-shading techniques to HiRISE data. The modeled topography of small-scale reliefs is based on the extrapolation of the abundance and spatial distribution pattern of geological features measurable in HiRISE data. Once we had completed the synthetic topography, we simulated camera images of the landscape. The intention is that these views may enable a more efficient planning of image acquisition and possibly a rapid interpretation of actual mission images that would help the determination of geological processes not identifiable from orbit. We determined that the cumulative fractional area covered by reliefs, i.e., float blocks and ridged outcrops, over the entire Oxia Planum landing site spans the range 0–30% with a mean abundance of reliefs of 7 ± 5%.

1. Introduction

One of the main objectives of the European Space Agency (ESA) and the Russian Roscosmos' ExoMars 2022 is the search for physical and chemical biosignatures through the *in situ* study of ancient, Noachian-aged (~4.1 Ga old), sedimentary material at the landing site, Oxia Planum (Vago *et al.*, 2017). This mission is part of a program (Vago *et al.*, 2015) that also includes the Trace Gas Orbiter (TGO), launched in 2016 (Svedhem et al., 2018). ExoMars 2022 will deliver a landing platform and a rover to the red planet, each hosting a suite of scientific instruments. Organic compounds are likely to be protected from the damaging radiation environment prevailing on the martian surface only if buried in the subsurface for long periods. The ExoMars rover will characterize the subsurface with a sounding radar, a neutron detector, and a spectrometer hosted in the rover drill—the latter is capable of reaching 2 m depth (Ciarletti *et al.*, 2017; De Sanctis *et al.*, 2017; Mitrofanov *et al.*, 2017). Samples collected by the drill will be analyzed by three successive analytical instruments to characterize their mineralogy, chemistry and any organic compounds (Bibring *et al.*, 2017; Goesmann *et al.*, 2017; Rull *et al.*, 2017). A suite of proximity (*i.e.,* surface remote sensing) instruments will investigate the geologic context: a panoramic camera (PanCam), a close-up high-resolution imaging camera (CLUPI) and a near infrared point spectrometer (Coates *et al.*, 2017; Josset *et al.*, 2017; Korablev *et al.*, 2017). PanCam consists of a set of stereo cameras named PanCam WAC (Wide Angle Cameras) and a High Resolution Camera (HRC) (Coates *et al.*, 2017). Each PanCam WAC projects a field of view (FOV) of 38°x38° into a 1024x1024 pixels wide detector. A filter wheel is used to acquire multispectral images in the visible wavelength. PanCam HRC projects a FOV of 4.8°x4.8° into a 1024x1024 pixels wide detector and makes use of a Bayer filter in front of the sensor to enable color imaging. Camera used for engineering purposes are the NavCam, located close to PanCam at the top of the mast, and LocCam located at a height of about 1 m at the bottom of the mast and fixed at an angle of 18° downward (Silva et al., 2013). NavCam and LocCam are identical stereo cameras that use a detector 1024x1024 pixels in size with a FOV of 68°x68°. The CLUPI camera has a FOV of 12°x8° (14° diagonal) and is equipped with a 2652x1768x3 pixels sensor composed of 3 stacked layers of pixels (red, green, and blue) for color acquisition (Josset et al., 2017). CLUPI is mounted on the drill so that its height and angle with respect to the horizon is variable. In addition, different FOV can be achieved with the use of mirrors.

The ExoMars platform and rover will perform complex engineering and scientific operations. The principal interactions with the geological environment required for engineering purposes include: touchdown with the platform legs, imaging the landing area for determining its geographic coordinates, deployment of two sets of rover ramps, rover egress, rover drive (~60 meter) to exit the descent engine blast contamination zone, close approach of the rover to an outcrop, surface/deep drilling and sample extraction, sample crushing, autonomous navigation for several tens of meter. For scientific purposes, knowledge of the surrounding geological environment is a key requirement for science planning, *e.g.,* to understand the subsurface stratigraphy and identify target depths where samples may be rich in organic compounds. The subsurface stratigraphy will be elucidated by integrating and interpreting data from subsurface-sensing instruments (the radar, neutron spectrometer, and drill-mounted infrared spectrometer) together with observations of the surface geological environment (from PanCam, ISEM and CLUPI). Performing combined science in this manner will maximize what can be learned about the geologic history of drilled samples.

Knowledge of the geological environment needs to span a range of spatial scales, from the tens of meters (*e.g.,* terrain slope during platform touchdown), to the centimeter scale (*e.g.,* wheel/soil interactions) in order to plan and perform the variety of operations. A thorough characterization of the local geology in its *sensu largo,* including, *e.g.,* material strength, grain size distributions, composition, cannot be attained before the actual mission. However, we can obtain a considerable amount of advanced information by concentrating on the topography of the terrain. The topography datasets for NASA missions are constructed with stereo-photogrammetry using High Resolution Imaging Science Experiment (HiRISE) imaging (McEwen et al., 2007). HiRISE Digital Terrain Models (DTMs) have a best ground sampling resolution of ~1 m (Golombek et al., 2018). Ancillary information on rock abundance is calculated using HiRISE imaging at the meter scale and a model dependent extrapolation to the centimeter scale (Golombek and Rapp, 1997).

The missing coverage in spatial resolution, especially in the range critical for the safety and traversability of lander and rover missions, *e.g.,* below HiRISE DTM resolution, is illustrated in Figure 1. Planetary surface topography represents the cumulative effect of geologic processes operating over different spatial- and time-scales. Generally, slope distributions are skewed towards steeper slopes at shorter baselines. Parameterizing the relationship between slope distribution and baseline (*e.g.,* by fitting values of the Hurst exponent, Rosenburg et al., 2011) permits the investigation of general topographic trends (Aharonson et al., 2001), represented by the power law scaling of slope abundance with baseline. A schematic of this relationship is illustrated in Figure 1. Also plotted in Figure 1 is the ground sampling resolution that is possible using different Mars topographic datasets, and the types of geological features responsible for the topographic expression. There is a spatial domain below ~1 m where the slope distribution cannot be directly constrained with available data. Given the typical ground clearance and mobility performance of Mars landers and rovers, it is this domain, between a few cms and 1 m, that is critical to assess landing safety and terrain traversability.

This challenge has been considered in the work of Martin et al. (2014) for the case of airless bodies, like the Moon, where the terrain morphology is dominated by impact craters. In Martin et al. (2014), the regional topography below the resolution of the data-based DTM is modeled with a purely theoretical fractal approach. The local topography due to impact craters is obtained following two models: one for the shape of the initial crater and another for the shape of the crater after diffusional degradation. Van Wal (2018) and Tardivel et al. (2014)

addressed a similar subject for small bodies with the frequency of blocks following a power law distribution.

For Mars, studies have been performed recently to increase the spatial resolution and reliability of DTMs. Among other studies (e.g, Gehrke, 2006, O'Hara and Barnes, 2012, Gupta et al., 2014), the works of Jiang et al. (2017), Wohlfarth et al. (2018) and Hess et al. (2019a), used the stereo and shape-from-shading techniques (*e.g.,* Shao et al., 1991) to improve Martian DTMs obtained with the stereo-photogrammetry method. Later, these methods have also been applied to HiRISE imagery (*e.g.,* Doute and Jiang, 2019; Hess et al., 2019b). The ground sampling resolution of such high-resolution DTMs is ~0.25 m, and the smallest resolved features are blocks of 0.7 m in width (Hess et al., 2019b).

In order to tackle the lack of topographic information at the centimeter level in the latter DTM, we have developed a synthetic topography built by combining two datasets. The synthetic topography is calculated by adding the topography of small-scale reliefs (*e.g.,* meter and sub-meter sized boulders) onto the high-resolution DTM. Importantly, the spatial pattern and abundance of small-scale reliefs follows geological units (Figure 2). Because the geological units are mapped by taking advantage of the highest resolution possible (*i.e.,* segmented HiRISE), the resulting topography is more representative of the actual terrain than has been the case in previous approaches (*e.g.,* Martin et al., 2014 for the Moon). In this article we will first present the technique employed for calculating the high-resolution DTM, followed by the method used in the construction of topography and pattern of the small-scale reliefs. We will then produce an example of a synthetic topography and explain its validation and performance (model vs. *in situ* rocks). Finally, cases using the synthetic topography and ancillary products, *e.g.,* rock abundance map, will be presented and discussed.

2. Method

2.1 Used dataset

Here we briefly present the technique that has been used to produce the high-resolution DTMs. The reader is encouraged to consult Hess et al. (2019b), and references therein, for a more thorough description. A common approach to improve the quality of planetary DTMs relies on the refinement of an initial DTM with the means of Shape and Albedo from Shading (SfS). Various methods have been devised with this principle such as Grumpe and Wöhler, 2014, Grumpe et al. 2014, Wu et al. 2017, Jiang et al. 2017, Alexandrov and Beyer 2018, Hess et al. 2019b. The initial DTM can be either generated from laser altimetry data or more highly resolved stereo-photogrammetric methods. The initial constraint ensures an accurate absolute height while SfS can account for slopes and details on small scales. Using an initial stereo DTM, SfS also allows to reduce the well-known artifacts produced by the block-matching method and pixel locking (Gehrig and Franke, 2016) effect in stereo-photogrammetric products. In our case, this leads to an effective ground sampling resolution equal to the pixel scale of the original image, *e.g.,* 0.25 meter (hereafter m) for HiRISE images.

The application of the shading procedure requires compensating for the effects of the atmosphere. The atmospheric parameters of the combined reflectance and atmospheric model are estimated by performing a nonlinear regression between the radiance data of the HiRISE imagery and the initial stereo DTM. Based on an initial stereo DTM that is very accurate for low and medium frequency components (*i.e.*, on a larger and medium spatial scales) the SfS procedure iteratively refines the surface. At each resolution level, accurate modeling of the reflectance behavior and the influence of the atmosphere, both mainly based on the Hapke model (Hapke, 2002), is employed to change the orientation of the surface facets such that the difference between measured and modeled reflectance values is minimized in the least square sense (Hess et al., 2019a). Additionally, regularization terms are employed to solve the ill-posed problem (Shao et al. 1991, Grumpe et al. 2014). Combining the accurate photogrammetric reconstruction with the proper slope estimation that is performed by the SfS, the advantages of both approaches can be harnessed. The accuracy of this procedure has been studied on the MRO/Context Camera (CTX) resolution using HiRISE stereo images as ground truth (*e.g.,* Hess et al. 2019a). The vertical accuracy achieved with this method was, in many cases, well below 2 m at a pixel resolution of 6 m/pixel (hereafter m/px). If the implications of this vertical accuracy vs. spatial resolution relationship are directly extrapolated to HiRISE images (capable of a maximum resolution of 0.25 m/px), for which, unfortunately, no ground truth comparison is possible before landing, the implied vertical accuracy can be estimated to be in the decimeter range.

2.2 Technique for the topography and spatial pattern of small-scale reliefs

The reliefs detectable in HiRISE images are ~1 m to several m wide features that typically correspond to rootless blocks (*e.g.,* boulders) or to topographic ridges (*e.g.,* outcrops). In other publications these features are referred to as ‘rocks’. However, because Oxia Planum has a considerable fraction of small ridges in addition to boulders (Quantin-Nataf et al., 2020, Ivanov et al., 2020), we use the more general term ‘reliefs’. Note that from an engineering point of view, rootless boulders or ridges can be considered identical; *e.g.,* they can be equally dangerous at touchdown. The detection technique is based on shadows cast by features and closely follows the approach described in Golombek *et al.* (2003). The major difference in this study resides in the shadow segmentation method. The detection algorithm follows the following steps: (i) dataset preparation, (ii) calculation of derived products and shadow segmentation, (iii) estimation of the size of reliefs casting shadow at the m-scale, (iv) extrapolation of relief abundances at the sub-m scale. The technique has been developed based on visual investigation of a few hundred reflectance profiles across shadows (Figure 3a) cast by a variety of landforms (*e.g.,* blocks, ridges, crater rims, dunes, mesas) over a variety of terrains (*e.g.,* of varying albedo, aeolian cover, bedrock exposure) and with different ranges of digital numbers corresponding to different instrument conditions. The sun-synchronous orbit of MRO yields images with approximately constant illumination geometry.

2.2.1 Data preparation

HiRISE data products require pre-processing before applying the detection algorithm. HiRISE images from the Planetary Data System (PDS) are geographically registered and calibrated to I/F cos(i), with i denoting the average incidence angle of the image. The image is divided into 250 m x 250 m^2 (1000 px x 1000 px) sub-frames. Each sub-frame is rotated in order to have the sub-solar azimuth consistently at 270°W.

2.2.2 Shadow segmentation

The following procedures are applied to each sub-frame.

(1) A so-called “shadow depth” (SD) frame is calculated. This frame detects decreases in reflectance independently of the local mean albedo. It exploits the property of a strong and spatially limited decrease in reflectance due to a small-scale shadow (Figure 3a). The calculation uses the parameter:

$$\text{depth} = (R_{\text{continuum}} - R_{\text{shadow}}) / R_{\text{continuum}} \quad \text{(eq. 1)}$$

where R_{shadow} is the reflectance of the sub-frame pixel located at (x,y). $R_{\text{continuum}}$ is a mean reflectance outside the shadow calculated with vertical and horizontal pixels located at a distance *d* from the considered pixel (x,y). Three shadow depth frames are calculated with d = 5, 7, 9 pixels named $SD_{d=5}$, $SD_{d=7}$, $SD_{d=9}$, respectively.

(2) Each SD frame is segmented with the maximum entropy thresholding (*e.g.,* Kapur et al., 1985). Note that Golombek *et al.* (2008) applied the same thresholding to reflectance sub-frames and not to shadow depth frames. Each SD frame leads to a pixel mask that identifies pixels in shadow.

(3) Pixels identified with shadow in each SD frame (i.e., $SD_{d=5}$, $SD_{d=7}$, $SD_{d=9}$) are merged into a single pixel mask. The use of three different SD masks allow to detect both small (~1 m size) and large (~5 m size) shadowed regions.

(4) Isolated pixels with shadow are removed. Our visual investigation confirmed that single-pixel detections are most frequently noise that does not represent shadow.

(5) The derived frame detects strong decreases in reflectance in the spatial range spanning from 1 m to several m. We found that such decreases could also be mimicked by albedo pattern, usually dark dunes on bright bedrocks. Therefore, an additional frame is calculated to partially avoid such pattern. By visually studying the shadows detected with shadow frames, we found that the reflectance profile of shadow in the illumination direction is characterized by an abrupt decrease in reflectance occurring within about three pixels (Figure 3a). Thus, we calculate a frame ($SD_{d=1}$) with the same principle of the depth parameter, with, however, a distance d=1 and in the horizontal (illumination) direction only. The frame $SD_{d=1}$ is used in the next step.

(6) Contiguous pixels are identified in the mask. To partially avoid false positives due to albedo pattern, only groups of pixels for which the $SD_{d=1}$ frame contains an abrupt decrease in reflectance ($SD_{d=1}>0.05$) are retained.

2.2.3 Estimation of the size of reliefs

The width of each remaining group is measured perpendicularly to the illumination direction. This width is assumed to define the size of the relief. The shadow length measured in the illumination direction is used to estimate the height of the feature, assuming it rests on a flat surface. We found that for sizes 2.5 m and larger, depressions of impact craters and escarpments start to dominate the detections. Disentangling blocks from other features is beyond the capability of this method, therefore the decision was taken to disregard all detections having size bigger than 2.5 m, as implemented in Golombek *et al.* (2012). As shown further below, this cutoff does not affect the measurements at smaller sizes. At this stage, the size and location of all small-scale topographic features across the frame are determined (Figure 4).

2.2.4 Extrapolation of relief abundances at the sub-meter scale

In order to estimate the abundance of features at the centimeter scale, we adopt the technique described in and Golombek et al. (2003, 2008). The area where the extrapolation is done can be either a sub-frame or a geological unit. Here we describe the technique using a sub-frame. The use of a geological unit is described in section 2.3. Our approach is based on a correlation between sub-meter abundances, as observed at the Viking lander sites, and the corresponding meter-scale HiRISE observations (Golombek et al., 2003). This correlation has been confirmed to be valid also for other sites (Golombek et al., 2008), although not for all (e.g., Heet et al., 2009). The variety of geological processing controlling reliefs formation, coverage, and erosion is such that a single model is not sufficient to describe their abundance across the entire martian surface. If developed, improved context-dependent models might be used in the future. The fraction of surface covered by rocks with diameters equal to or greater than some value D for various total rock coverage fractions is defined by:

$$F(D) = k \exp[-q(k)D] \qquad \text{(eq. 2)}$$

$$q(k) = (A + B/k) \qquad \text{(eq. 3)}$$

with A=1.79 and B=0.152 (Golombek and Rapp, 1997). The parameter k is the total rock coverage or the cumulative fraction of surface covered by blocks of all sizes. The parameter q(k) defines the rate of drop-off in the exponential function at large blocks diameter. We implemented the technique with the following two steps.

First, for each sub-frame, the cumulative size frequency distribution of features per m^2 is calculated in the size range 1.5–2.5 m. The lower boundary is set by the spatial resolution (Sefton-Nash et al., 2016, Golombek et al., 2003), whereas the upper boundary is defined in section 2.2.3.

Second, a best fit between the measured cumulative size frequency distribution and the model distributions of Golombek and Rapp (1997) is determined (Figure 3b) and results in the estimation of the parameter k. Because in this work we include ridges in addition to rocks, we refer to the parameter k*, to distinguish it from the k calculated in previous studies for rocks only.

2.3 Technique for the development of synthetic topography

The construction of synthetic topography necessitates the segmentation of the region of interest into geological units. The unit boundaries are mapped visually using single HiRISE images in the same manner as in geological mapping, with the ESRI ArcGIS software. A unit in a geologic map is assumed to have been formed by a single geologic process or event (although it may have been the subject of erosion and or other diagenetic effects thereafter). Thus, the relief abundance it contains is most likely to be spatially homogeneous. Because these units can be very small (area ~100 m^2) the abundance of reliefs may prove too low to obtain a reliable fit to the size frequency distribution to the Golombek and Rapp (1997) model. In such cases, the abundance is evaluated visually, by comparing the unit with look up maps, *i.e.,* of larger areas having known homogeneous abundance (Figure 5). Only with this approach was it possible to estimate the abundance of reliefs for extremely small areas (~100 m^2). This approach is taken at the expense of the abundance precision. We estimate that the latter decreases relative to what can be achieved in areas ≥ 60,000 m^2 (*e.g.,* sub-frame area) to about ±5%.

The final step to produce synthetic topography consist in the addition of small-scale reliefs to the stereo and shape-from-shading HiRISE DTM. In order to do this, we performed a cubic interpolation to generate a DTM with a spatial resolution of 0.01 m based on the HiRISE height information (0.25 m). Small scale reliefs for each unit were randomly distributed starting from larger to smaller diameters according to the size frequency distribution calculated in previous steps. In order to avoid spatial overlaps, reliefs were iteratively randomly redistributed if they would superpose existing reliefs or exceed unit boundaries. We considered simple shapes for the reliefs, *i.e.,* square in planar view and aspect ratio of 0.5 (height/width), as well as a dome shaped structure.

3. Results

We obtained small relief abundance maps across Oxia Planum where sufficient data was available (Figure 6). Manual geological mapping to produce the final synthetic topography is a time-consuming effort. Thus, we limited our analysis to an area close to the center of the ExoMars 2020 landing ellipses with sufficient topography for our display purposes (Figure 7). The touchdown target for the ExoMars 2022 landing site remains the same as for a launch in 2020, only the azimuth of the dispersion ellipses are shifted. Because a large portion of the landing ellipse is relatively flat, the synthetic topography was calculated in an area chosen to highlight the effectiveness in reconstructing topographic reliefs. This area is not representative of the most likely landing terrain. It is instead characterized by slopes ≤ 8° (over a few m) and relief abundances up to a cumulative fractional area of 20%.

4. Discussion

Here we first discuss the algorithm for rock detection, followed by a discussion of the reconstructed synthetic topography.

The precision of the automatic identification of blocks was tested by estimating the cumulative fractional area at the landing sites of the Viking Landers 1 and 2, Mars Pathfinder, Phoenix, Mars Science Laboratory (Gale Crater), Mars Science Laboratory candidate site (Eberswalde), and Insight. There is an agreement within 5 % between our algorithm and literature estimates (Golombek and Rapp, 1997; Golombek et al., 2008, 2012) (Figure 8). This is the largest (*i.e.,* worst case) difference because the comparison could not be made with exactly the same dataset. For some counts presented in the literature, the precise location of the count area was not indicated, the size of the area is different, or the image (HiRISE observation number) is unknown and might be different. Other discrepancies must arise from the image enhancement and the detection algorithm itself. For example, we use a best-fit approach to estimate the cumulative fractional area, whereas the Golombek et al. (2008) method employs lookup tables. In order to test our algorithm with actual rock abundances, we compare in Table 1 the cumulative fractional area of rocks 1) from lander observations, 2) from our algorithm, and 3) from the canonical Golombek et al. (2008) method. The landing sites having sufficient rock abundance for which it is possible to perform estimates with HiRISE images are few; they are limited to the Viking landers and Mars Pathfinder locations. As in the previous comparison, the size of the count areas is different between the lander and the orbital observations.

We have found that at Oxia Planum very strong differences in reflectance (~0.1 in lambertian albedo) can occur within very small areas (~5 m^2). These variations in reflectance are equal or larger than that between shadowed and non-shadowed surfaces. These very small areas consist of aeolian deposits (*e.g.,* longitudinal dunes) of dark material on top of high reflectance and dust-free bedrock. In some instances, the dark aeolian material can be found filling narrow fractures of the bedrock. The stark and spatially abrupt reflectance difference found in these small areas leads to artifacts. We have found that both the algorithm for the high resolution DTM and for the shadow detection are affected by this type of feature. The extreme similarity between these features and shadow casting reliefs, and their relative rarity within Oxia Planum, led us not to consider an *ad hoc* workaround to avoid them.

Another potential issue has its origin in HiRISE images. Although HiRISE images may appear without artifacts in a visual investigation, and are thus usable for photo-geological analysis, they might have distinct contrast that lead to differences in shadow detection. This is shown in some HiRISE images in Figure 6. The reason for such differences might have an origin in the instrument level (gain), or be related to atmospheric conditions, although clouds or dust coverage were not visually identifiable. Differences in rock abundance in juxtaposing HiRISE images is also seen in other studies (Figure 9a in Golombek et al., 2012).

A comparison of the synthetic topography with actual data can be done with a single dataset, *i.e.,* images acquired by the Mars Descent Imager (MARDI) onboard the NASA Curiosity rover (Malin et al., 2017). The camera acquired optical images of the surface during the landing phase with a ground sampling resolution at and below the centimeter scale. The image in Figure 9a has a ground sampling resolution of 0.1 m/px, in Figure 9c of ~0.05 m/px. Units common to both images are topographically flat, likely representing aeolian deposits, and rough units composed of ridges with varying amounts of blocks. We note how in both synthetic and actual images the flat units are free of blocks. Shallow depressions as small as 5 m in width are present at Gale crater and correspond to subdued impact craters. The synthetic image present shallow (<10 cm deep, ~5 m wide) irregular depressions, but do not have the circular form typical of impact craters. Such small impact craters might not be fully resolved, or they might not be present at the location of the synthetic image. Using HiRISE images, Golombek *et al.* (2012) estimated a cumulative fractional area (CFA) covered by blocks < 10% at the Curiosity landing site. By qualitatively comparing the abundance of rocks in the MARDI image (Figure 9b,d) with the synthetic patterns, we find that the CFA in the 100 x 100 m^2 area centered at the Curiosity touchdown location varies between 5% and 2.5%.

5. Applications

5.1 Landing site safety

The mean cumulative fractional area occupied by shadow-casting obstacles at the Oxia Planum landing site is 7 ± 5%. This estimate agrees with manual counts performed in discrete locations as part of the landing site qualification tasks (*e.g.,* Sefton-Nash et al., 2016). On a qualitative basis, there is agreement between the spatial distribution of blocks mapped manually (Pajola et al., 2017) and with our automatic procedure. Oxia Planum has two major geological units: a relatively smooth unit with a near infrared signature indicating the presence of Fe/Mg phyllosilicates, and an overlaying, dark, relatively rougher (at the tens of m scale) unit without clay spectral components (Quantin-Nataf et al., 2020, Ivanov et al., 2020). In terms of abundance of small-scale reliefs, we find that both units have a considerable range of variation and that the clay-rich unit has only slightly lower relief abundances (Figure 10). Thus, the bulk area of the two units can be considered similar from an engineering point of view (*e.g.,* landing safety and traversability). On the other hand, the wind-eroded edges of the clay-free unit terraces tend to be cliff-forming.

5.2 Simulated camera images

Model images of the synthetic terrain, as if taken by the ExoMars rover cameras, namely NavCam, LocCam, PanCam and PanCam HRC (high-resolution camera), are shown in Figure 11. Note that these images are complementary to previous PanCam image simulations that used a three-dimensional rendering system for the ExoMars rover without any information on its surroundings (Miles et al., 2020). Figure 12 shows similarly modelled CLUPI images. The scene depicted in our simulations represents a site of bedrock exposure due to aeolian erosion, with consequent rock fragmentation, and localized aeolian deposition of sand (*e.g.,* Ivanov et al., 2020). These simulated scenes are based on a geological context found in previous, although not in all, Martian missions. They provide a starting point from which geological analysis of future actual images can be developed. Any difference with actual images would signal the action of additional geological processes that could not be hypothesized based on the information derived from orbital investigations (Stack et al., 2016). For example, if the modeled image corresponds to a landscape dominated by surficial basaltic deposits reworked by impact and eolian processes (as observed, for example, by the rover Spirit at Gusev Crater, Grant et al., 2004), then the artificial topography will be mostly characterized by blocks with an aspect ratio of ~0.7 (b/a) and ~0.5 (c/a), where a>b>c are the axis in order of decreasing length (e.g., Michikami et al., 2016). If, instead, in the mission image we observe regions with stacked rocks having a very low height/width ratio, these might hint to an outcrop recording a different geological process (*e.g.,* fluvial sediments like those observed by Curiosity in Yellowknife bay, Grotzinger et al., 2014). Such an outcrop, comprised of rocks that formed in the presence of liquid water, would represent a region of prime science interest for a mission like ExoMars. Obviously, this hypothetical preliminary insight from rock morphology only will need to be confirmed by observations of rock textures and other properties. The comparison between the actual and modelled images during a mission, where a visual discrepancy between the two images can quickly signal the presence of an outcrop comprised of fluvial sediment could be helpful to recognize regions of interest where to drive the rover. We clarify that this approach is not proposed in substitution of – or for automatizing – a traditional visual investigation of the acquired images, but only as an additional tool to increase the chances of not missing interesting outcrops. Compositionally different lithologies are likely to occur in the same, morphologically homogeneous, geological landscape and would not be detected with the approach described above.

Moreover, the modelled PanCam HRC and CLUPI images may prove useful for interpreting distant features that are poorly discerned in rover mission images (*e.g.,* far away objects or blocks that are partially obscured by others). Indeed, the three-dimensionality of distant features is sometimes difficult to assess. For example, from a single image taken under specific light conditions, it might be difficult to conclude whether two visually discrete features are actually boulders with dissimilar compositions or the perceived variation is only an artifact created by different illumination of the same rock formation. A modeled image of the same field of view might be helpful for discriminating between the two possible interpretations. Figures 11 and 12 allow to better understand and appreciate the imaging capabilities of the cameras regarding features likely to be present at the site. Because the cameras are pointing in the same direction, we find that the set of cameras have complementarity and partial redundancy (NavCam with PanCam, PanCam HRC with CLUPI) with respect to geological targets. We note that the color capabilities of HRC and CLUPI are not taken into account here.

5.3 Traversability planning

We developed a simple traversability map based on the approximation that rover motion progress vs. time is a function of the local slope and the height of the small-scale reliefs it traverses. Rover speed decreases with increasing slope abundance according to an exponential function defined such that speed tends toward zero for a local slope of 30° or for a relief height of 30 cm. In this way, we computed a transformation from the synthetic topography into a traversability map. We considered the example case in which two potential science targets have been identified on the slope of a small hill. The rover speed on a horizontal surface was set at 4 cm/s (Zhou et al., 2013). Given the same rover starting point (at the beginning of sol), the objective of the test was to calculate the travel time to the two locations. We found that the paths, optimized for travel time, to the two targets have different lengths (95 m, 113 m) and can be negotiated in approximately the same time (6h0min vs. 6h8min, respectively) due to roving across different types of units (Figure 13).

6. Conclusions

The scientific and engineering work to be performed with the ExoMars Rosalind Franklin rover will require knowledge of the topography at a spatial resolution that cannot be reached using cameras on orbiting spacecraft. The planning of activities, such as landing site characterization and testing of rover mobility on a representative terrain, is limited by the lack of a topographic map at the centimeter scale. We have shown that a geologically meaningful extrapolation of topography at relevant spatial resolutions can be achieved by combining high-resolution HiRISE DTM, HiRISE segmentation based on geologic units, and a model of small-scale relief abundances.

To calculate the synthetic topography for this work, we performed the detection of small-scale reliefs on the Oxia Planum landing site. Our work indicates that the cumulative fractional area covered by small-scale features is 7±5%, consistent with manual counts carried out at discrete locations.

In the near future, we expect to improve the visual realism of our simulated rover camera images by considering more natural shapes for the small-scale reliefs based on the topography of outcrops found on terrestrial analog sites.

Synthetic topography can be used also for missions involving long traverses, such as NASA's Mars 2020 Perseverance rover (*e.g.,* Williams et al., 2020). The helicopter on Mars 2020 (Golombek et al., 2020) will capture images at the centimeter resolution. This will provide an ideal dataset to further test and improve this technique.

7. Acknowledgments

O.R. was supported by an appointment to the ESA Research Fellow Program at the European Space and Technology Center (ESTEC) and by a Sofja Kovalevskaja Award of the Alexander von Humboldt Foundation.

8. Data availability

The synthetic topography data is freely available at the following address or upon request at Ottaviano Ruesch: https://uni-muenster.sciebo.de/s/N6yEw5nM20Yd4H9.

9. Table and figures captions

Table 1. Cumulative fractional area covered by rocks (in %) at three landing sites. Estimates from ground truth observations and two HiRISE-based extrapolation methods.

Figure 1. Schematic plot showing the applicability of factors and DTM types at different spatial scales (top), and the approximate placement on slope and size axes of common Mars geologic features (bottom). The need to fill the data gap at ~sub-meter scales, where features are still large enough to be relevant to landing and traversability, is highlighted. This domain is where synthetic topography can play a role.

Figure 2. Workflow for the calculation of a synthetic topography using inputs from HiRISE images, a stereo and shape from shading technique, and a model for the abundance of small-scale reliefs.

Figure 3. (a) Reflectance profile across a block and its shadow from HiRISE data. Illumination direction from the left. (b) Cumulative fractional area covered by small reliefs larger than a given diameter, as a function of the relief diameter. Curves represent the distribution of reliefs at 5, 10, 20, 30, 40 % from Golombek and Rapp (1997). Data points are from a 500 by 500 m^2 area. Downturn at low diameter is a resolution effect.

Figure 4. (a) Shadow mask of a 500 by 500 m^2 area. (b) Contours (in red) of identified shadow belonging to blocks overlaid on an HiRISE frame.

Figure 5. Representative areas for different abundances of shadow-casting reliefs expressed as k* (see text for definition). Abundance maps are color-coded (See figure 5 for labeling). Abundance maps are 500 m wide. HiRISE close-ups are 110 m wide.

Figure 6. Color-coded maps of cumulative fractional area of reliefs superimposed on a High Resolution Stereo Camera (HRSC) mosaic (Gwinner et al., 2016, 2019). The landing site ellipses for a 2020 launch are shown for different landing probability (light gray: 3-sigma, medium gray: 2-sigma, dark gray: 1-sigma). The azimuth of the ellipses is a function of the launch date.

Figure 7. Perspective view of a shaded relief from the synthetic topography at a spatial resolution of 1 cm over an area of 100 x 100 m^2. Red contour lines are shown every meter.

Figure 8. Comparison between cumulative fractional area covered by reliefs (k*) at different landing sites on Mars, measured in this study and in literature works. The values used in the comparison are taken from plots and maps in the literature and are shown here with an uncertainty of ±2.5 %.

Figure 9. Qualitative comparison of the spatial pattern of roughness units between the synthetic topography at Oxia Planum shown as shaded relief (a,c) and a Mars Descent Imager (MARDI) image acquired during descent of the Curiosity rover at Gale crater (b,d). Common units are topographically flat and blocks-free ('F') and rough with varying amounts of blocks ('B'). Depressions are labeled 'D'. The synthetic image has units of different cumulative fractional area covered by blocks (CFA). The CFA at the Curiosity landing site has been estimated with HiRISE images to less than 10 % (Golombek et al., 2012). See main text for discussion.

Figure 10. Distribution of the abundance of small-scale reliefs (k*) for the two major geological units at the Oxia Planum landing site: a clay-rich unit (blue) and a dark unit (red).

Figure 11. Modelled images by the ExoMars rover cameras. (a) NavCam, FOV 68°x68°. (b) LocCam, FOV 68°x68°. (c) One of two stereo images acquired by PanCam WAC, FOV 38°x38°. (d) PanCam HRC, FOV 4.8°x4.8°. All images are 1024x1024 pixels in size. Percentage values indicate fractional area covered by rocks. Dashed lines indicate boundary between different rock densities. The facet of a rock identifiable in all images is shown with a red box. The synthetic topography is illuminated with a light source at an angle of 60° above the horizon. Sky shown in white.

Figure 12. (a) CLUPI image in the geological environment survey mode with stowed drill and use of the primary mirror. The height of CLUPI is 40 cm. The entire FOV of 12°x8° is pointing 20° downwards from a horizontal plane and ahead of the rover. The synthetic topography is illuminated with a light source at an angle of <10 ° above the horizon to highlight cm-sized reliefs. Image 2652x1768 pixels in size. (b) Diagram of the position of CLUPI and the drill (yellow) corresponding to image acquisition in (a). (c) CLUPI image taken after the drill is lifted and rotated, and is pointing horizontally from a 1 m height. Image 2652x1128 pixels in size restricted to a FOV of 12°x5° using the second mirror. Here the synthetic topography is

illuminated with a light source at an angle of 60 ° above the horizon. (d) Diagram showing the lifted and rotated drill enabling CLUPI images at various elevations. Computer-aided design rendering (b) and (d) by Space Exploration Institute.

Figure 13. Rover traversability analysis on a color-coded synthetic topography. The triangle symbol is the start point and stars are target locations. Green lines are paths with the shortest traverse time calculated by considering the slope of the terrain and obstacles by small-scale reliefs.

10. References

Aharonson, O. et al., (2001), Statistics of Mars topography from the Mars Orbiter Laser Altimeter: Slopes, correlations and physical Models, Journal of Geophysical Research, Vol. 106, E10, pp. 23723-23735, doi: 10.1029/2000JE001403.

Alexandrov, O. and Beyer, R. A., (2018), Multiview Shape-From-Shading for Planetary Images. Earth and Space Science, 5(10), 652-666.

Bibring, J.-P. et al. (2017) ‘The MicrOmega Investigation Onboard ExoMars’, Astrobiology, 17(6–7), pp. 621–626. doi: 10.1089/ast.2016.1642.

Ciarletti, V. et al. (2017) ‘The WISDOM Radar: Unveiling the Subsurface Beneath the ExoMars Rover and Identifying the Best Locations for Drilling’, Astrobiology, 17(6–7), pp. 565–584. doi: 10.1089/ast.2016.1532.

Coates, A. J. et al. (2017) ‘The PanCam Instrument for the ExoMars Rover’, Astrobiology, 17(6–7), pp. 511–541. doi: 10.1089/ast.2016.1548.

De Sanctis, M. C. et al. (2017) ‘Ma_MISS on ExoMars: Mineralogical Characterization of the Martian Subsurface’, Astrobiology, 17(6–7), pp. 612–620. doi: 10.1089/ast.2016.1541.

Douté, S., & Jiang, C. (2019). Small-Scale Topographical Characterization of the Martian Surface With In-Orbit Imagery. IEEE Transactions on Geoscience and Remote Sensing, 58(1), 447-460. doi:10.1109/TGRS.2019.2937172.

Gehrig, S., Franke, U., (2016). Stereovision for ADAS. Handbook of Driver Assistance Systems, Springer International Publishing, chapter 21, 495–524.

Gehrke, S., (2006)., Geometric and radiometric modeling of the martian surface based on object space matching and photoclinometry. ISPRS Arch., 36(B4), 1031-1036.

Goesmann, F. et al. (2017) 'The Mars Organic Molecule Analyzer (MOMA) Instrument: Characterization of Organic Material in Martian Sediments', Astrobiology, 17(6–7), pp. 655–685. doi: 10.1089/ast.2016.1551.

Golombek, M., and Rapp., D., (1997), Size-frequency distributions of rocks on Mars and Earth analog sites: Implications for future landed missions, J. Geophys. Res., 102, E2, p. 4117-4130, doi:10.1029/96JE03319.

Golombek, M. P., Haldemann, A. F. C., Forsberg-Taylor, N. K.,, et al., (2003), Rock size-frequency distributions on Mars and implications for Mars Exploration Rover landing safety and operations, J. Geophys. Res., 108, E12, 8086, doi:10.1029/2002JE002035

Golombek, M., Huertas, A., Marlow, J., et al., (2008), Size-frequency distributions of rocks on the northern plains of Mars with special reference to Phoenix landing surfaces, J. Geophys. Res., 113, 3, E00A09, doi: 10.1029/2007JE003065.

Golombek, M. et al. (2012), Detection and characterization of rocks and rock size-frequency distributions at the final four Mars Science Laboratory landing sites, Mars, 2(7), pp. 1–22. doi: 10.1555/mars.2012.0001.

Golombek, M., Grott, M., Kargl, G., et al., (2018), Geology and Physical Properties Investigations by the InSight Lander, Space Science Reviews, 214, 5, 84, doi:10.1007/s11214-018-0512-7.

Golombek, M., Balaram, J.; Maki, J.; Williams, N.; Grip, H.; Aung, M., (2020), Mars Helicopter on the 2020 Rover Mission, LPSC, abstract n. 2096.

Grant, J. A., Arvidson, R., Bell, J. F., Cabrol, N. A., Carr, M. H., Christensen, P., ... & Golombek, M., (2004), Surficial deposits at Gusev crater along Spirit rover traverses. Science, 305(5685), 807-810.

Grotzinger, J. P., Sumner, D. Y., Kah, L. C., Stack, K., Gupta, S., Edgar, L., ... & Milliken, R. (2014), A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars. Science, 343(6169).

Grumpe, A., Belkhir, F., Woehler, C., (2014), Construction of lunar DEMs based on reflectance modelling. Advances in Space Research, 53, 1735-1767, doi: 10.1016/j.asr.2013.09.036.

Grumpe, A., Woehler, C., (2014), Recovery of elevation from estimated gradient fields constrained by digital elevation maps of lower lateral resolution. ISPRS, 94, 37-54, doi:10.1016/j.isprsjprs.2014.04.011.

Gupta, S., Paar, G., Muller, J.-P., et al., (2014), Fusion and Visualization of HiRISE Super-Resolution, Shape-from-Shading DTM with MER Stereo 3D Reconstructions, AGU fall meeting, abstract nr. P41D-3955.

Gwinner, K. et al., (2016), The High Resolution Stereo Camera (HRSC) of Mars Express and its approach to science analysis and mapping for Mars and its satellites, Planetary and Space Science, http://dx.doi.org/10.1016/j.pss.2016.02.014

Gwinner, K., Bostelmann, J., Dumke, A., et al., (2019), Characteristics of the HRSC Mars Chart (HMC-30) and its Quality of Co-Registration with the MOLA Reference, EPSC-DPS Joint Meeting 2019, Geneva, Switzerland, abstract nr. EPSC-DPS2019-2006.

Hapke, B., (2002), Bidirectional reflectance spectroscopy: 5. The Coherent Backscatter Opposition Effect and Anisotropic Scattering. Icarus, 157, 523–534.

Heet, T. L., Arvidson, R. E., Cull, S. C., Mellon, M. T., & Seelos, K. D, (2009), Geomorphic and geologic settings of the Phoenix Lander mission landing site. Journal of Geophysical Research, 114.doi:10.1029/2009je003416.

Hess, M., Wohlfarth, K., Grumpe, A., Wöhler, C., Ruesch, O., Wu, B., (2019a), Atmosphere-ically compensated shape from shading on the martian surface: Towards the perfect digital terrain model of Mars, ISPRS, Volume XLII-2/W13, doi.org/10.5194/isprs-archives-XLII-2-W13-1405-2019

Hess, M., Wohlfarth, K., Ruesch, O., Wöhler, C., & Grumpe, A. (2019b), High Resolution Digital Terrain Model for the Landing Site of the Rosalind Franklin (ExoMars) Rover, EPSC-DPS2019.

Ivanov, M., Slyuta, E.N., Grishakina, E.A., Dmitr, A.A., (2020), Geomorphological Analysis of ExoMars Candidate Landing Site Oxia Planum, Solar System Rsearch, Vol. 54 No. 1, doi: 10.1134/S0038094620010050.

Jiang, C., Douté, S., Luo, B., Zhang, L., (2017), Fusion of photogrammetric and photoclinomeric information for high-resolution DEMs from Mars in-orbit imagery. ISPRS Journal of Photogrammetry and Remote Sensing, 130, 418-430.

Josset, J.-L., Westall, F., Hofmann, B. A., et al., (2017), The Close-Up Imager Onboard the ESA ExoMars Rover: Objectives, Description, Operations, and Science Validation Activities, Astrobiology, 17(6–7), pp. 595–611. doi: 10.1089/ast.2016.1546.

Kapur, J., Sahoo, P., Wong, A., (1985), A new method for gray-level picture thresholding using the entropy of the histogram, Comput. Visual Graph. Image Processes, 29(3), 273– 285, doi:10.1016/0734-189X(85)90125-2.

Korablev, O. I. et al. (2017), Infrared Spectrometer for ExoMars: A Mast-Mounted Instrument for the Rover, Astrobiology, 17(6–7), pp. 542–564. doi: 10.1089/ast.2016.1543.

Malin, M. C., Ravine, M. A., Caplinger, M. A., et al., (2017), The Mars Science Laboratory (MSL) Mast cameras and Descent imager: Investigation and instrument descriptions, Earth and Space Science, Volume 4, Issue 8, pp. 506-539, doi: 10.1002/2016EA000252.

Martin, I., Parkes, S., Dunstan, M., (2014), Modeling cratered surfaces with real and synthetic terrain for testing planetary landers, IEEE Transactions on Aerospace and Electronic Systems, vol. 50, issue 4, pp. 2916-2928, doi:10.1109/TAES.2014.120282.

McEwen, A., Eliason, E. M., Bergstrom, J. W., (2007), Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE), J. Geophys. Res., 112, E5, E05S02, doi:10.1029/2005JE002605.

Michikami, T., Hagermann, A., Kadokawa, T., et al., (2016), Fragment shapes in impact experiments ranging from cratering to catastrophic disruption, Icarus, 264, 316–330, 10.1016/j.icarus.2015.09.038

Miles, H. C., Gunn, M. D., Coates, A. J., (2020), Seeing Through the "Science Eyes" of the ExoMars Rover, IEEE Computer Graphics and Applications, doi:10.1109/MCG.2020.2970796

Mitrofanov, I. G. et al., (2017), The ADRON-RM Instrument Onboard the ExoMars Rover, Astrobiology, 17(6–7), pp. 585–594. doi: 10.1089/ast.2016.1566.

O'Hara, R., & Barnes, D., (2012), A new shape from shading technique with application to Mars Express HRSC images. ISPRS journal of photogrammetry and remote sensing, 67, 27-34.

Pajola, M., Rossato, S., Baratti, E., (2017), Boulder abundances and size-frequency distributions on Oxia Planum-Mars: Scientific implications for the 2020 ESA ExoMars rover, Icarus, 296, 73-90, doi:/10.1016/j.icarus.2017.05.011.

Quantin-Nataf, C., et al., (2020), The geology of Oxia Planum, Mars, article under revison.

Rosenburg, M. A., O. Aharonson, J. W. Head, M. A. Kreslavsky, E. Mazarico, G. A. Neumann, D. E. Smith, M. H. Torrence, M. T. Zuber, (2011), Global surface slopes and roughness of the Moon from the Lunar Orbiter Laser Altimeter, J. Geophys. Res., 116, E02001, doi:10.1029/2010JE003716.

Rull, F. et al., (2017), The Raman Laser Spectrometer for the ExoMars Rover Mission to Mars, Astrobiology, 17(6–7), pp. 627–654. doi: 10.1089/ast.2016.1567.

Sefton-Nash, E., Bridges, J. C., Kissick, L., Butcher, F., Donnelly, P., Piercy, J. D., Vago, J. L., Loizeau, D., Lorenzoni, L., Grindrod, P. M. and Balme, M., (2016), Characterizing Rock Abundance at ExoMars Landing Site Candidates. In: 47th Lunar and Planetary Science Conference, Abs. # 1918.

Shao, M., Chellappa, R., & Simchony, T., (1991)., Reconstructing a 3-D depth map from one or more images. CVGIP: Image Understanding, 53(2), 219-226.

Silva, N., Lancaster, R., Clemmet, J., (2013), ExoMars rover vehicle mobility functional architecture and key design drivers, proceeding of Advanced space technologies for robotics and automation (ASTRA), ESTEC, Noordwijk, The Netherlands.

Stack, K. M., Edwards, C. S., Grotzinger, J. P., Gupta, S., Sumner, D. Y., Calef III, F. J., ... & Le Deit, L. (2016), Comparing orbiter and rover image-based mapping of an ancient sedimentary environment, Aeolis Palus, Gale crater, Mars. *Icarus*, *280*, 3-21.

Svedhem, H., Vago, J.L., (2018), ExoMars Trace Gas Orbiter reaches science orbit, p.16932, 20th EGU General Assembly, EGU2018, Vienna, Austria.

Tardivel, S., Scheeres, D. J., Michel, P., Van wal, S., Sanchez, P., Contact motion on surface of asteroid, (2014), Journal of spacecraft and rockets, doi:10.2514/1.A32939

Vago, J. et al. (2015) 'ESA ExoMars program: The next step in exploring Mars', Solar System Research, 49(7), pp. 518–528. doi: 10.1134/S0038094615070199.

Vago, J. L. et al. (2017) 'Habitability on Early Mars and the Search for Biosignatures with the ExoMars Rover', Astrobiology, 17(6–7), pp. 471–510. doi: 10.1089/ast.2016.1533.

Van Wal, S., (2018), High-Fidelity Simulation of Small-Body Lander/Rover Spacecraft, PhD thesis, University of Colorado.

Williams, N. R., Stack, K. M., Calef, F. J., Sun, V., Williford, K., Farley, K., Mars 2020 Geologic Mapping Team, (2020), Photo-Geologic Mapping of the Mars 2020 Landing Site, Jezero Crater, Mars, LPSC, abstract n. 2254.

Wohlfarth, K., Liu, W. C., Wu, B., et al. (2018), High Resolution Digital Terrain Models of the Martian Surface: Compensation of the Atmosphere on CTX Imagery, Lunar and Planetary Sci. Conf. abstract nr.2498.

Wu, B., Liu, W. C., Grumpe, A., & Wöhler, C., (2018)., Construction of pixel-level resolution DEMs from monocular images by shape and albedo from shading constrained with low-resolution DEM. ISPRS journal of photogrammetry and remote sensing, 140, 3-19.

Zhou, F., (2014), Simulations of mars rover traverses, Journal of Field Robotics 31(1), 141–160, doi:10.1002/rob.21483