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Fusion of photogrammetric and photoclinometric information for high-resolution DEMs from Mars in-orbit imagery

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Abstract High-resolution Digital Elevation Models (DEMs) of the Martian surface are instrumental for studying the red planet : characterizing geological objects, generating synthetic images, normalizing illumination conditions on images, and modeling local meteorology. Our work addresses the problem of producing DEMs for regions of interest on Mars using available in-orbit imagery, typically ≈1000 km2 in area, while insuring a ≈10 meters vertical accuracy and a spatial accuracy which is comparable to that of the imagery. A method is proposed that combines photogrammetric and photoclinometric approaches in order to retain their mutual advantages. According to experiments using Mars Reconnaissance Orbiter Context Camera (CTX) images, the proposed method is indeed able to produce DEMs satisfying the previous requirements, with less artifacts, better surface continuity, and sharper details than the photogrammetric method when it is used alone.

Introduction In the literature, there are two approaches for the production of regional to local DEMs (≈10^2-10^5 km2 in area) based on images, namely photogrammetry (or stereo) and photoclinometry (or shape from shading, SFS). Photogrammetric methods need at least two images capturing the same region of interest but from a different viewpoint. It is based on the effect of parallax that can be exploited by triangulation. The core part of photogrammetry is matching, pair of pixels each belonging to one image, and solving a system of collinearity equations involving the image coordinates of the matched pixels as observations, the 3D coordinates of the corresponding point on the scene, and camera parameters. Photoclinometric methods, can derive surface gradients (i.e. slopes) from the intensity variation of an image, therefore allow to produce a DEM from a single image if the surface can be reconstructed from these gradients by integration for example. The two approaches have their own advantages and drawbacks. Photogrammetric methods are fast, able to directly produce DEMs with absolute heights and have good comparative performances for large scale objects of interest. However, the matching of pixels needs recognizable local intensity patterns on both pair images that, consequently, need to be acquired with comparable surface and illumination conditions. As for photoclinometric methods, no matching of pixels is needed, thus preserving small details in the DEM. However, the method is relatively complex and slow to converge, requires integration of gradient fields, and cannot produce absolute heights. Furthermore the modeling of intensity spatial variations in the image entails a priori information on the bidirectional reflectance properties of the surface. We propose a new fusion algorithm of photogrammetric and photoclinometric information to retain their mutual advantages.

Method Our choice is motivated by the existence of an independent, well-known and capable photogrammetric tool, which is open to public and keeps updating, i.e. NASA Ames Stereo Pipeline (ASP) (Shean et al., 2016). In the proposed algorithm (Fig. 1), the photoclinometric scheme subsequently takes this "original" DEM as an input along with the image and refines it at small scales by inverting a radiative transfer model that depicts the image intensity field for a given topography, atmospheric, illumination and viewing conditions. Another specific aspect of the algorithm is that the model is inverted with an optimization procedure containing two regularization terms. The first one insures that variables describing the height field on the one hand and the gradients on the other hand are separated for a better numerical stability. The second regularization term insures that the algorithm retains the properties of the original DEM at large scales. It also speeds up the convergence and constrains the solution space. Finally, the novelty of the proposed method is multiple. First the intensity model integrates an innovative radiative transfer scheme. Second the model also uses a realistic description of the bidirectional reflectance distribution function (BRDF) of the surface, as an anisotropic semi-empirical kernel-based model, namely the Ross-Thick Li-Sparse (RTLS) model. The

kernel weights of the RTLS model for a given scene are retrieved using the Mars-Reco algorithm (Ceamanos et al., 2013) applied to multi-angular sequences of hyperspectral images by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) if they are available.

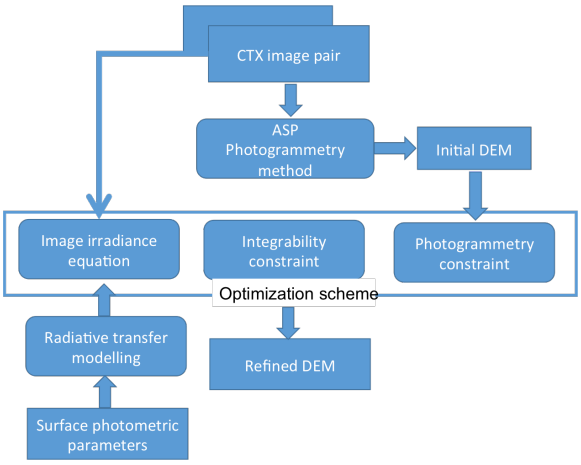

Figure 1: The flowchart of the proposed method.

Experiments and discussion

To test the proposed method, we have performed experiments with different CTX datasets of increasing complexity. By complexity we mean the fraction of missing values and the density of artifacts in the original DEM produced by ASP as well as the degree of spatial inhomogeneity and contrast affecting the intrinsic albedo of the surface. The test datasets are composed of CTX images that have been cropped according to regions of interest pixels wide so that the results are allowed to be presented in greater details. For a representative case, Fig. 2 shows results respectively obtained using only ASP and the proposed method. Individual data points collected by the Mars Orbiter Laser Altimeter (MOLA) are accessible to the public and their estimated absolute heights can be used as a reference for validating the refined DEM by calculating the Root Mean Square Error. Besides an index is calculated to evaluate the similarity of the original left CTX image and the reflectance image simulated from the refined DEM. Compared with the result using ASP, the result of the proposed method has less artifacts, its surface become more continuous, its edges become sharper and more details are revealed. The result of the proposed method also has smaller RMSE and better similarity index that stresses the consistency of its good performance.

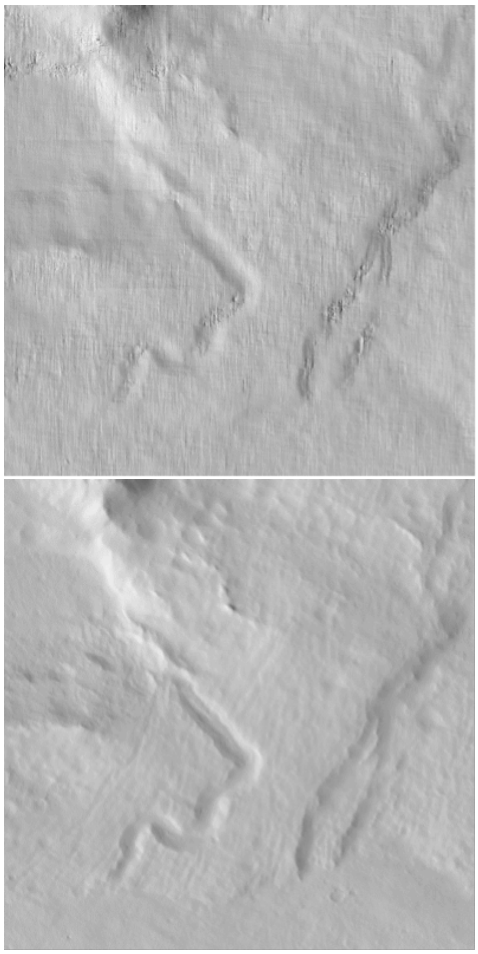

Figure 2: Results obtained using ASP only (top) and the proposed method (bottom). These shaded image sare produced when the sun azimuth is 256.63° and the sun elevation is 50.20°, same as for the left component of the CTX image pair.

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