Fusion of photogrammetric and photoclinometric information for high-resolution DEMs

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INTRODUCTION

High-resolution Digital Elevation Models (DEMs) of the Martian surface are instrumental for studying the red planet : geological investigations, meteorology simulations, hazard assessment for landers and rovers. It is also critical for orthoimage generation, for improving the precision of surface reflectance retrieval, and for spectral unmixing of hyperspectral images. We aim at producing DEMs 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 (ref.[1]) is proposed that combines photogrammetric and photoclinometric approaches in order to retain their mutual advantages.

Two approaches for producing DEMs based on images :

Photogrammetry (or stereo): exploits by triangulation the effect of parallax differing between two images capturing the same scene but from a different viewpoint. The matching of pixels needs recognizable local intensity patterns on both pair images (difficult). Fast, able to directly produce DEMs with absolute heights. Good performances for large scale objects.

Photoclinometry (or shape from shading, SFS): derives surface gradients (i.e. slopes) from the intensity variation of an image. Therefore allows to produce a DEM from a single image if the surface can be reconstructed from these gradients by integration. Relatively complex and slow to converge, requires a priori information on the bidirectional reflectance properties of the surface. Cannot produce absolute heights, but preserve small details in the DEM.

METHOD

The proposed method exploits photogrammetric and photoclinometric information in a successive way (Fig.1)

The NASA Ames Stereo Pipeline (ASP) produces an "initial" DEM from an image pair by photogrammetry. The photoclinometric scheme subsequently takes this “initial” **z0** DEM as an input along with one of the images **I** and refines the former at small scales. For that purpose an optimization procedure finds the topography **z** that best explains the image intensity field:

$$\mathbf{z} = \underset{\mathbf{p},\mathbf{q},\mathbf{z},\beta}{\arg\min}\,\mathbf{E}$$

$$\text{with } \mathbf{E} = \underbrace{\frac{1}{2}\left(\beta\cdot\mathbf{R}(\mathbf{p},\mathbf{q})-\mathbf{I}\right)^2}_{\text{“image intensity constraint”}} + \overbrace{\underbrace{\frac{\lambda_1}{2}\left[\left(\mathbf{p}-\mathbf{z}_x\right)^2+\left(\mathbf{q}-\mathbf{z}_y\right)^2\right]}_{\text{“integrability constraint”}} + \underbrace{\frac{\lambda_2}{2}\left(\mathbf{W}\cdot\mathbf{z}-\mathbf{W}\cdot\mathbf{z}_0\right)^2}_{\text{“photogrammetric constraint”}}}^{\text{regularization}}$$

The procedure contains three terms :

Image intensity constraint: a radiative transfer model **R** depicts the intensity **I** measured by the sensor for given atmospheric, illumination and viewing conditions and for a given gradient **(p,q)** of the surface height according to the horizontal and vertical axis of the image. The model uses a realistic description of the bidirectional reflectance distribution function (BRDF) of the surface, as an anisotropic semi-empirical kernel-based model, the RTLS model:

$$\rho\left(s_0,s,p,q\right) = k^L + k^G f_G\left(s_0,s,p,q\right) + k^V f_V(s_0,s,p,q)$$

The function $\mathbf{f_G}$ and $\mathbf{f_V}$ are predefined generic kernels, and $\mathbf{k_L}$, $\mathbf{k_G}$, and $\mathbf{k_V}$ are their weights which are defined by the surface reflective properties. The kernel weights for a given scene are retrieved using the Mars-Reco algorithm (ref.[2]) applied to multi-angular sequences of hyperspectral images by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) if they are available.

“integrability constraint”: insures that variables describing the height field **z** on the one hand and the gradients **(p,q)** on the other hand are separated for a better numerical stability. $\mathbf{z_x}$ and $\mathbf{z_y}$ are the calculated gradients derived by convolution of **z** with derivative filters.

“photogrammetric constraint”: insures that the algorithm retains the properties of the original DEM **z0** at large scales. It also speeds up the convergence and constrains the solution space. **W** is a mask to filter out the points where ASP fails.

$\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$ are parameters to balance the two regularization terms.

Validation: The estimated absolute heights of individual data points collected by the Mars Orbiter Laser Altimeter (MOLA) can be used as a reference for validating the refined DEM by calculating the Root Mean Square Error (RMSE). Besides an index (GMSD) is calculated to evaluate the similarity of the original left CTX image and the reflectance image simulated from the refined DEM.

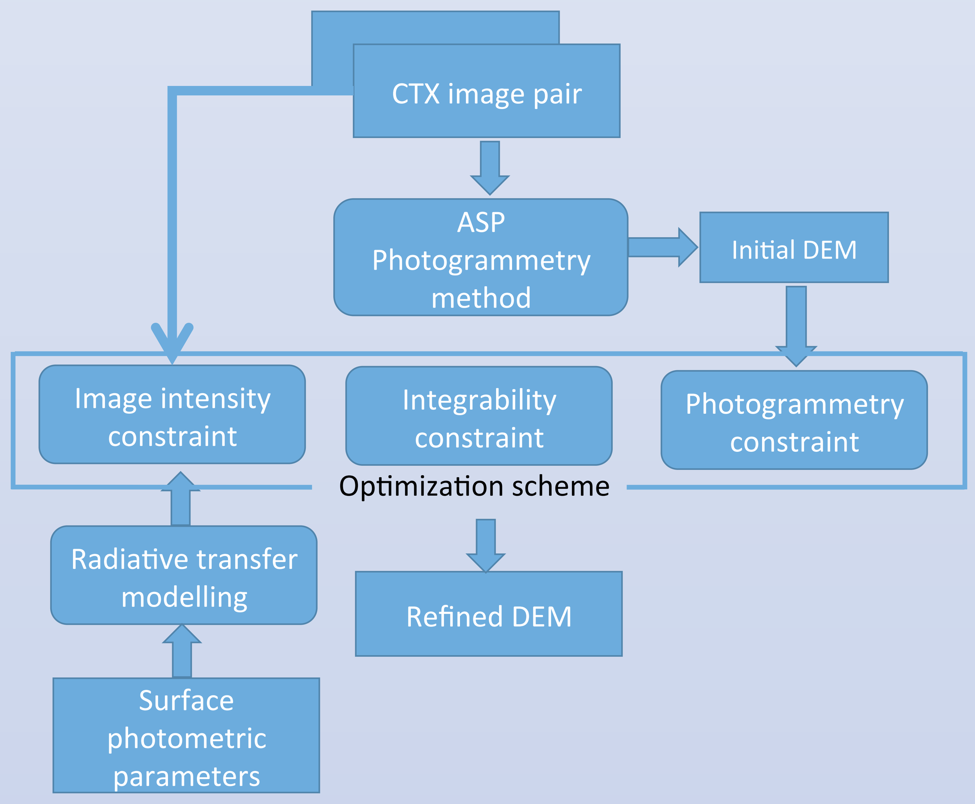

Fig.1 *The flowchart of the proposed method*

CONCLUSIONS

Compared to using photogrammetry alone, 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 has smaller RMSE with MOLA control points although it also depends on the accuracy of the initial DEM produced by ASP and the accuracy of the RTLS kernel weights.

The photoclinometric scheme introduces in some cases artifacts in the DEM (Fig.4) in the form of “plane waves” of limited amplitude affecting the topographic field **z** with a “direction of propagation” approximately orthogonal to the original direction of the sun in the image. This phenomenon is likely due to a relative invariance of the intensity R(p,q) for some specific variations of p and q.

NUMERICAL ASPECTS

We propose a two step strategy to avoid introducing wavy artifacts with the photoclinometric scheme:

(i) solving the optimization problem in a framework rotated against the image with one axis in the direction of the sun and one axis in the direction perpendicular to the sun.

(ii) attributing different weights to the two terms (p-z_x) and (q-z_y) in the “integrability constraint”, the latter being more penalized than the former because it contains all the artifacts.

Preliminary tests indicate that the artifacts can be substantially reduced if the slopes aligned with the sun represent a minority in the real topography.

The convergence speed of our algorithm is satisfactory and its complexity is approximately linear with the image size. Besides it is fully vectorized and a tiling strategy is implemented for processing the image by several processes in parallel. The computation time for producing a full scale DEM is a few hours (stereo and SFS).

EXPERIMENTS

We test the method with different CTX datasets of increasing complexity. Results are presented both for large (Fig.2) and for small regions of interest 800x800 pixels wide (Fig.3 and Fig.4).

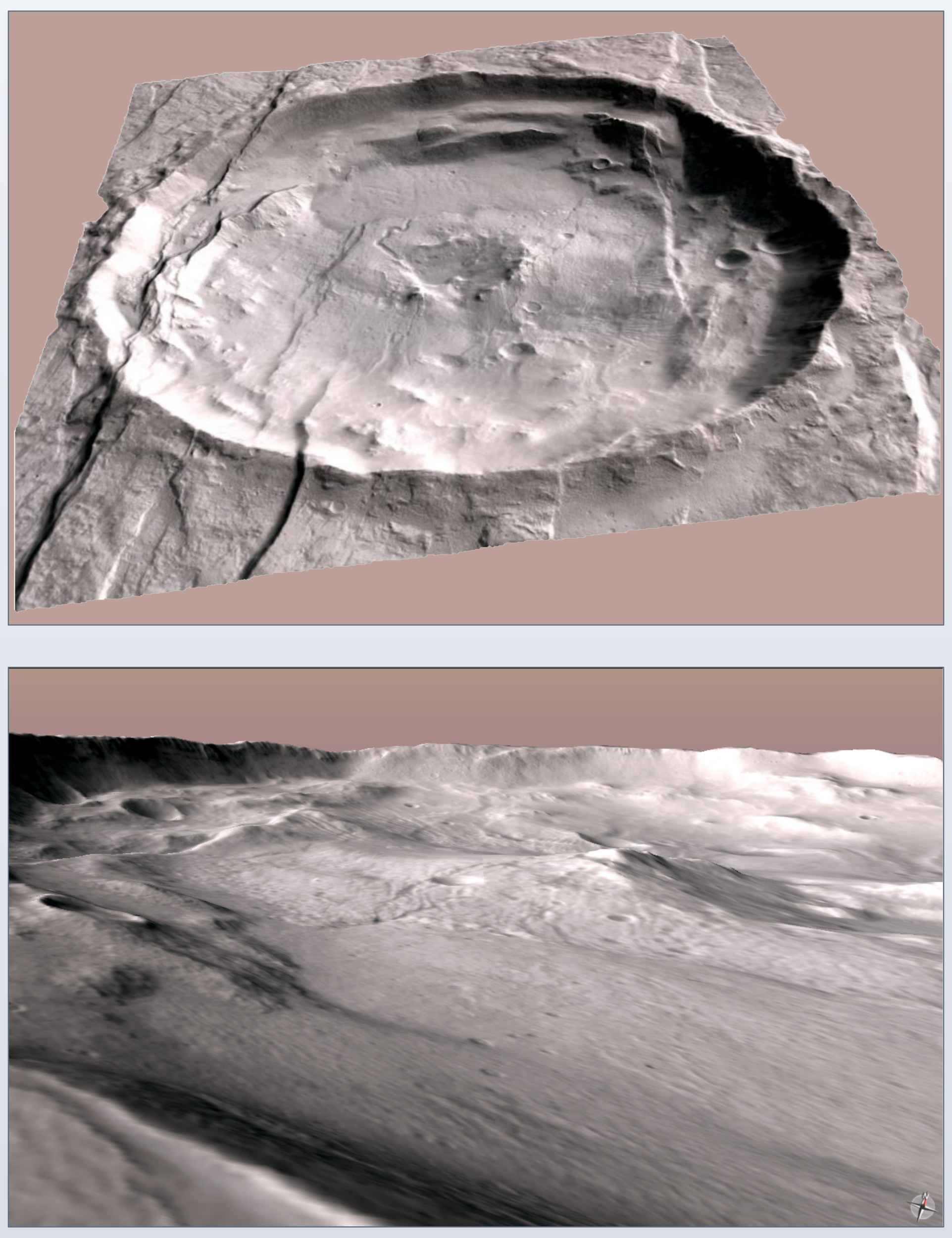

Fig.2 illustrates the capability of our algorithm to process large CTX left and right images 5000x5000 pixels wide corresponding to ≈1000 km2 in area.

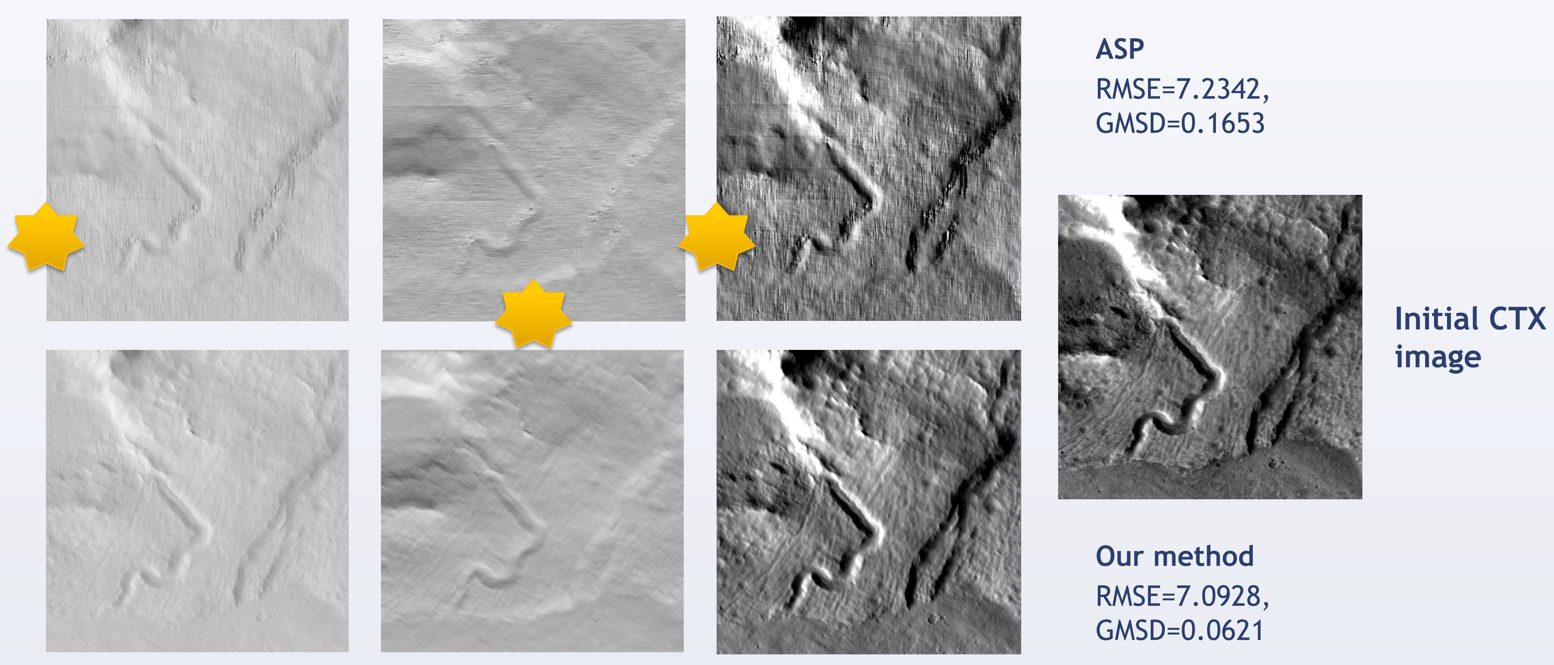

Fig. 3. Results obtained using ASP only (first line) and the proposed method (second line). The shaded images in the first column are produced when the sun azimuth is 256.63° and the sun elevation is 50.20°, same as for the CTX image. For the shaded images in the second column, the sun azimuth is 180° and the sun elevation is 45°. In the third column , the image simulated using the corresponding DEMs is presented and ought to be compared with the initial image. Note also the respective values of the RMSE and GMSD indicators.

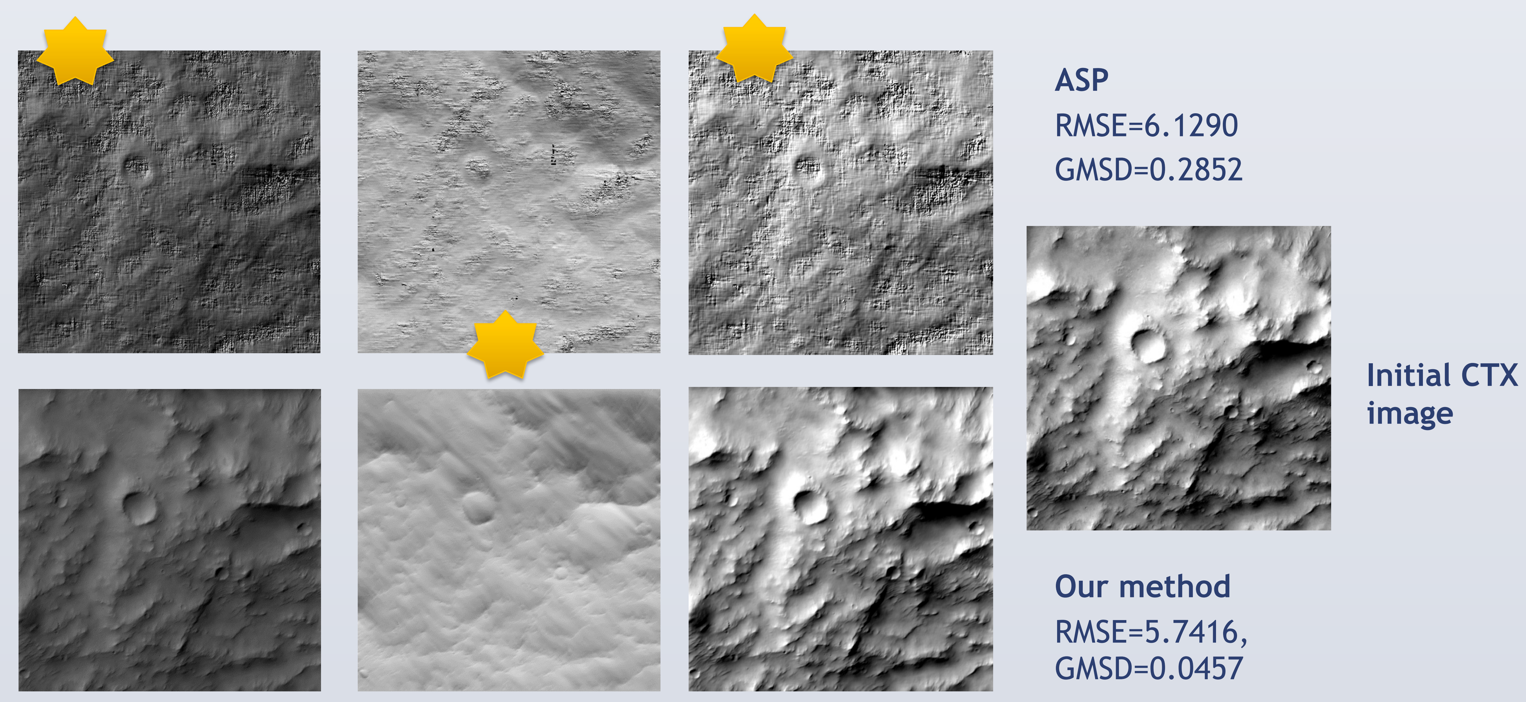

Fig. 4. Same type of products as in Fig.3 but for another scene. The shaded images in the first column are produced when the sun azimuth is 312.70° and the sun elevation is 19.57°, same as for the left component of the CTX image pair.

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