DE- AND RE-SHADING OF MARS EXPRESS HRSC IMAGE DATA FOR HOMOGENIZATION OF MAP RELIEF SHADING

E. Dorrer[a], H. Mayer[a], A. Ostrovskiy[a], S. Reznik[a], G. Neukum[b] and the HRSC Co-Investigator Team

[a] Institute for Photogrammetry and Cartography, Munich Bundeswehr University, Werner-Heisenberg-Weg 35,
D-85577 Neubiberg, Germany, egon.dorrer@unibw-muenchen.de

[b] (HRSC Principal Investigator), Institute for Earth Sciences, Freie Universitaet Berlin, Malteserstr. 74-100,
D-12249 Berlin, Germany, gneukum@zedat.fu-berlin.de

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ABSTRACT:

Within the Photogrammetry and Cartography Group (PCG) of the Mars Express HRSC (High Resolution Stereo Scanner Camera) Co-Investigator Science Team, the main task of which is the development and derivation of high quality cartographic and GIS products of the Martian surface, from the very beginning emphasis has been placed on complementing and improving the stereo-photogrammetric DEM by *Shape-from-Shading* (SFS) methods. This is possible due to the low textured surface of Mars – contrary to Earth. The paper discusses the present state of methodical and experimental research leading to a software prototype that is to be integrated in the general data processing package developed by the guiding Institute of Planetary Research of the German Aerospace Center (DLR). The paper first deals with the description of a novel process denoted *De-Re-Shading* (DRS) for the purpose of modifying illumination induced shades in image scenes of the Martian surface. Kernel is an SFS method known from Computer Visualization. The SFS-refined DEM will be the basis for subsequent modifications of image shades towards rigorous homogenization and optimization of relief shading in the digital ortho-image maps to be generated by the PCG. From a methodical view point SFS is described as a problem of Variational Analysis with constraints. The Conjugate Gradient method is employed to a direct solution of the extended discrete unconstrained minimization functional. Finally, first preliminary results utilizing appropriate real HRSC image data as well as MOC/MOLA data are presented. Despite certain limitations to the method and the preliminary development stage, the results confirm the considerable refinement potential of SFS for an approximate DEM.

1. INTRODUCTION

Automatic generation of digital image maps of the Martian surface is a major task of the Photogrammetry and Cartography Group (PCG) of the Mars Express HRSC Co-Investigator Science Team. HRSC (High Resolution Stereo Scanner Camera) is one of seven scientific instruments on the Mars Express Orbiter, all for the purpose of gathering data for geological, mineralogical, atmospheric, gravitational, and cartographic studies over a period of two years. Guided by the Institute of Planetary Research of the German Aerospace Center (DLR), science work within PCG – one of four HRSC groups – is carried out by eight institutions. Within the science data processing program the group's main task is the development of software for generating high quality cartographic and GIS products such as ortho-image maps of the surface of Mars. These products form the basis for further data derivates for a variety of science disciplines.

Having been set-off by a Russian Soyuz/Fregat launcher from Baikonur spaceport in Kasakhstan on 2 June 2003, the Mars Express space craft reached Mars on 27 December 2003 and, after ejection of the – later failing – Beagle 2 lander, started manoeuvring into a highly elliptical capture orbit from which it was transferred into its final operational near polar orbit. Orbiter science operations with systematic data transmission down to Earth began in mid January 2004. During the following few months a tremendous amount of image data at different resolutions and on different spectral channels were down-linked via the Deep Space Network. Low level data processing, i.e. mainly radiometric calibration, at the DLR institute began immediately, followed by first attempts of high level scientific 3D-processing from the three to five HRSC stereo channels. For the first time spectacular 3D-scenes of the Martian surface of medium to high resolution stereo imagery in color as well as instructive perspective views could be presented to the general community.

In our studies emphasis has been placed from the very beginning to complement photogrammetric image matching based object reconstruction by a *Shape-from-Shading* (SFS) approach. The principle of SFS was introduced and defined thirty years ago by B.K.P. Horn, the "father of SFS" (Horn, 1970). On Mars one of the prerequisites of SFS, viz. textureless surface, is largely fulfilled. Exactly on this type of surface, photogrammetric "*Shape-from-Matching*" (SFM) fails, therefore the two very different methods complement each other. In fact, SFS, as kernel of a novel process denoted *De-Re-Shading* (DRS), is capable of a substantial refinement of the Digital Elevation Model (DEM) obtained by stereo photogrammetry alone. Similar findings have already been discussed by several authors, e.g. (Dorrer, et.al., 1998), (Hashemi, et.al., 2002), (Rajabi, et.al., 2003), yet never have been applied under real conditions and on a bigger scale. This will be the case for the first time with Mars Express cartography. By exploiting additional information beyond primary HRSC image data, SFS for the first time will enable a distinct refinement of the DEM generated by photogrammetric matching. Despite the still preliminary and simplified approach to the problem complex, the results shown in this paper clearly demonstrate the potential of the employed method.

The extremely large number of elevations – equal to the number of elevation cells – as unknown parameters is apt to produce substantial performance problems. The aim is to employ an efficient numerical method guaranteeing processing time approximately proportional to image size. Limitations to the over-all process are mainly due to space-variant surface albedo, severe atmospheric disturbances, shadows and certain illumination conditions. It may therefore be envisaged that only a subset of Mars scenes will be amenable to data processing by De-Re-Shading.

The next section is devoted to a brief introduction into our general DRS approach. The fundamental SFS kernel will be described in some detail both from the mathematical and numerical points of view. After an account on the present implementation stage and future improvements emphasis will be placed upon a discussion of the experimental results so far obtained and conclusions to be drawn from them.

2. DE-RE-SHADING (DRS)

2.1 Conceptual Approach

The DRS process is based on the conditional comparison of the irradiance of an ortho-image (*E*) with the modelled radiance image (*R*) of the object scene; see the block diagram of Fig. 1. We assume that the ortho-image was derived from an original HRSC image (*I*) together with the orientation and calibration state of the camera (*C*) during the time of exposure and an intitial digital elevation model (*Z*) obtained by stereo photogrammetry (shape from matching SFM). The conditionality of the comparison stems from the constraint that the global difference between initial DEM and corrected DEM becomes minimal. Kernel is a Shape-from-Shading (SFS) method mostly known from Computer Visualization.

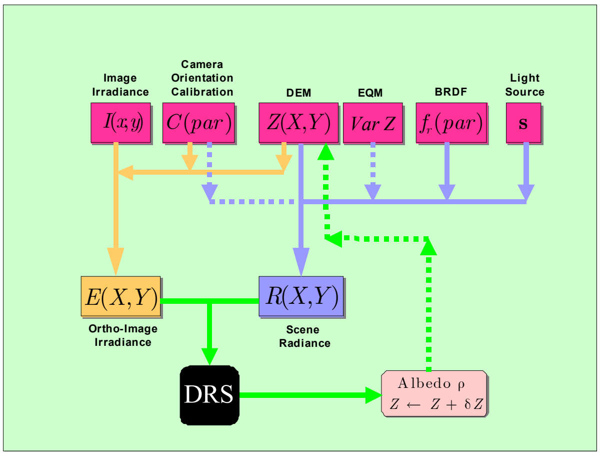

Figure 1. Block diagram of DRS data flow

Prerequisite for a definite solution is an initial DEM of sufficient quality. The stochastic model of the DEM may be given by the global elevation variance (*Var Z*) as elevation quality model EQM). Both initial DEM and EQM possess some potential for the derivation of space variant albedo. Other input parameters concern the BRDF (Bidirectional Reflectance Distribution Function), i.e. an assumed reflectance law, and the sun vector (*s*). The present experimental version utilizes constant BRDF, hence diffuse (Lambert) reflection. The corrected DEM may be used as new initial DEM thus defining an iterative process, although real improvements may be expected only if the ortho-image will be computed anew as well. Further, albedo is considered constant for each scene.

The dark solid lines indicate the present stage of the solution, the dotted lines have not yet been implemented, and the light solid lines belong to an a priori process external to SFS. Not shown in Fig. 1 is the mosaicking of neighboring scenes.

2.2 Shape from Shading (SFS)

Depending on numerous, partly merely estimable geometrical and physical factors such as surface reflectance, shadows, light source distribution, image resolution, accuracy of initial elevation map, etc., SFS applied to real-world imagery is a non-trivial, generally ill-posed problem. SFS has been and still is treated in an extensive mathematics and theory oriented literature covering mostly small and limited problems. An excellent survey is given by (Zhang et al., 1999). An important aspect concerns the coupling of deterministic and stochastic optimisation approaches (Crouzil et al., 2003) in order to determine optimal values for the penalty factors of the constraint terms.

From the methodical view point SFS is a problem of Variational Analysis with constraints. Historically such constraints were predominantly incorporated to ensure convergence to a somewhat smoothed solution in order to omit discontinuities and make them mathematically manageable (Horn, 1970). Although this is true in the continuous domain, for discrete data there is a resolution limit given by the pixel size. Real discontinuities can therefore not exist, hence smoothing regularization constraints become obsolete.

In our present SFS-approach the basic (continuous) equation is defined by the minimization (or optimisation) integral

$$J(Z) = \iint_{\Omega} \left[\left(E - \rho\, R \right)^2 + \lambda \left(Z - Z^{(0)} \right)^2 \right] dX\, dY \rightarrow \min \qquad (1)$$

taken over a scene Ω in the (X,Y)-plane. Equ.(1) is the unconstrained form of the constrained minimization functional, extended by the elevation constraint with a “penalty” factor λ. Z represents the surface of the desired DEM, $Z^{(0)}$ the initial DEM as approximation to $Z(X,Y)$ which is to be determined such that the functional $J(Z)$ becomes minimal. See Fig. 1 for the notation. $R = R(p,q)$ as modelled reflected scene radiance is a function of the surface slopes $p = Z_X(X,Y)$ and $q = Z_Y(X,Y)$. The scene albedo factor can be estimated by the expression

$$\rho = {\iint E\,R} \Big/ {\iint R^2} \qquad (2)$$

and λ is the ratio of the variances of E and $Z^{(0)}$, viz.

$$\lambda = \left(\sigma_E / \sigma_{Z^{(0)}} \right)^2 \qquad (3)$$

thus representing the global stochastic model part (Crouzil, et al., 2003).

Instead of establishing the Euler-Lagrange equations associated with Equ.(1) as, e.g., in (Dorrer, et al, 1998), and solve the discretized system of partial differential equations, we have solved the discretized Equ.(1) directly by variation of Z until the functional J is minimal. This is possible by expressing the slopes simply as the convolutions of constant difference filters, A and B, with Z, viz.

$$p(Z) = A * Z, \quad q(Z) = B * Z \tag{4}$$

Then the scene radiance is $R = R(p(Z), q(Z))$ and Equ.(1) becomes

$$J(Z) = \iint \left[(E - \rho R(Z))^2 + \lambda (Z - Z^{(0)})^2 \right] dX dY , \tag{5}$$

which may now be solved iteratively by the method of conjugate gradients (Shewchuck, 1994). Main advantages of CGM are that linearization of nonlinear functions is not required, convergence of the method normally is superlinear (Beckmann, et al., 2001), and Z will be determined indirectly when J approaches the minimum. Some prerequisites for CGM such as convexity of J follow from $Z^{(0)}$ being rather close to Z. In essence, CGM approaches the minimum by successively searching for line minimums along consecutive "conjugated" gradients

$$\nabla J = 2 \iint \begin{bmatrix} -\rho\,(E - \rho R(Z)) \big(R_p(Z) * A + R_q(Z) * B \big) \\ + \lambda (Z - Z^{(0)}) \end{bmatrix} dX dY \tag{6}$$

The principle of CGM is exhaustively explained in (Shewchuck, et al, 1994).

2.3 Present Implementation

The present experimental version of the DRS software under development is a preliminary stand-alone version written in C and runs both under MS-windows and Linux. In addition an independent APL2–version is used for testing and further evaluation purposes. It is expected that the final C–version will be integrated in a comprehensive software package developed by the DLR Co-Investigator team.

The still rudimentary property of the DRS version may be characterized by the following limitations:

- Lambert reflection (constant BRDF)
- Constant scene albedo factor
- No shadows
- No atmospheric correction
- Simplified stochastic model of the DEM
- Non-automated pre- and post processing
- Autmated SFS-kernel only
- Rectangular scene regions
- Local cartesian 3D-coordinate system.

Despite these limitation the refinement of an initial photogrammetric, i.e. SFM-derived, DEM is remarkable as will be demonstrated for two suitable scenes in the following section. It is of course envisaged to successively improve the present DRS version by dropping the limitations. This is however a tedious way requiring not only new theoretical ideas but also extensive experimental work with many different HRSC scenes.

3. DISCUSSION OF EXPERIMENTS

Prior to the availability of HRSC data we have first used a rectangular subsection of a Mars Global Surveyor MOC wide-angle scene (M000094 situated on Mars in the southern part of Icaria Planum at 95° W longitude and 41° S latitude) for which DLR had prepared the required ortho-image (Fig.2a) and associated MOLA-DEM. The latter is shown as modelled radiance image in Fig.2b and with 100-m contours in Fig.2c. As may be seen from Fig. 2b, due to the relatively wide gaps between adjacent MOLA profiles the DEM may only be considered as rough approximation to the real surface.

The ortho-image has size 476x402 with a pixel size of 232 m, thus covering an area of 110 km by 93 km. This yields a relatively small printing scale of 1:2'500'000.

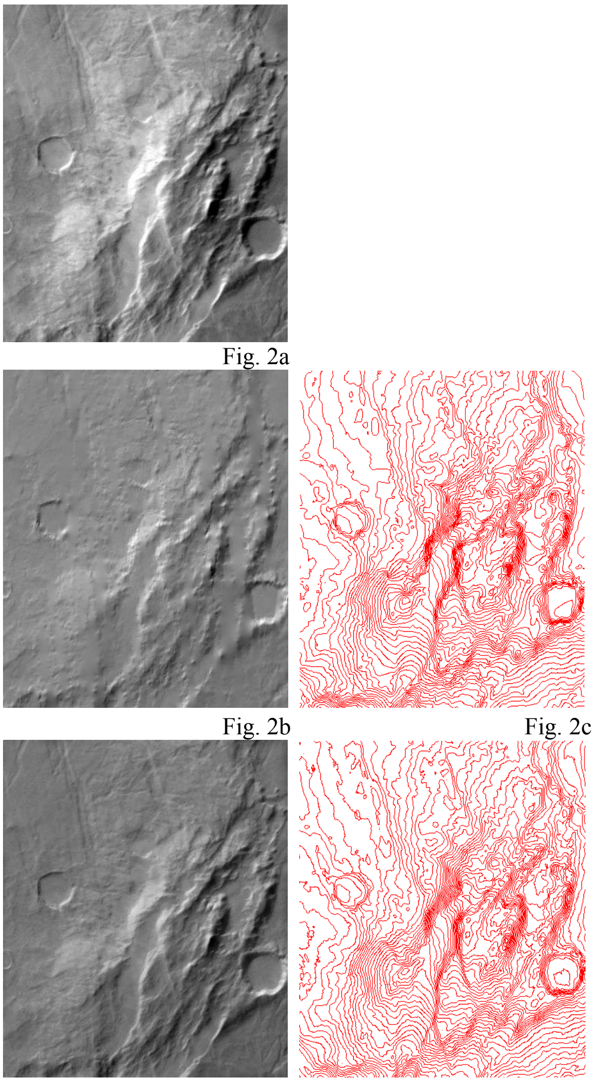

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Fig. 2e

Figure 2. MOC wide-angle scene 110 km by 93 km
at printing scale 1:2'500'000

The SFS-refined result after some 20 iterations is shown in Fig. 2d and Fig. 2e. In general the contour lines (Fig. 2e) derived from the SFS-refined DEM appear much more regularly, i.e. they are better correlated with each other. The surface appears smoother and more realistic. The modelled scene radiance (Fig. 2d) can hardly be distinguished from the original ortho-image (Fig. 2a). There are, of course, differences caused by the limitations of the present program version. The somewhat brighter appearance of Fig. 2a as compared to Fig. 2d is probably due to a slightly varying BRDF, i.e. deviation of the actual reflectance law from Lambert. Fig. 2a also suggests two distinct regions with different albedo factors. By applying only one albedo factor to the image data this brightness difference has been evened out thus leading to a duller and less bright result image. Further differences are caused by the few small shadow areas, since shadows were incorrectly treated as non-shadows.

A crucial point is the optimal value for the penalty factor. We processed the data with a series of different values. The one which intuitively and subjectively gave the most pleasing result was considered optimal (0.005). We are, however, still unable to comprehend its relationship with the underlying stochastic model as given by Equ.(3). Yet, some statistics of the differences between SFS-refined DEM and initial DEM may give an indication of the significance of the result. Realize that pixel size is 232 m.

Maximum difference:	279 m
Mean difference:	0.46 m
Minimum difference:	-265 m
Standard deviation:	32 m

Fig. 3 exhibits the main processing stages of a 150 by 150 pixel subsection of an HRSC scene taken on 24 February 2004 at 266 km altitude in orbit 143. Approximate location is 137° W longitude and 40° N latitude in the Acheron Fossae on the northern slope of Olympus Mons. The topographic surface is therefore generally inclined towards North. Illumination is somewhat from the south with 48° sun elevation. The ortho-image prepared by DLR is illustrated in Fig. 3a. It has been radiometrically enhanced for better detail recognition. With 100 m pixel size the scene covers an area of 15km by 15km. Printing scale is 1:400’000, hence more than 6-times larger than that of the MOC image. The corresponding DEM is shown as grey scale image in Fig. 3c. It was determined by the DLR data processing group by image matching (SFM) from the HRSC stereo channels at the original 30 m resolution level. The modelled scene radiance (Fig. 3b), however, shows enormous deficiencies in the DEM caused mainly by insufficient surface texture needed for SFM. Realize that Fig. 3b is supposed to appear as Fig. 3a! The contour lines of the SFM-determined DEM (Fig. 3d) may give an idea of the difficulties SFM has had for matching the image data.

Figs. 3e, 3f, and 3g show the same scene after SFS-refinement after 10 CGM-iterations. Despite some unwanted (and not yet comprehended) boundary effects visible mainly in the contour map (Fig. 3g), the resulting scene radiance (Fig. 3e) is much more alike the original ortho-image (Fig. 3a). Although there are – probably illumination induced – artefacts visible in the DEM-image (Fig. 3f) and other errors due to incomplete modelling, a dramatic improvement of the pure photogrammetric, i.e. SFM-derived, DEM is obvious. As to be expected (intuitively) the larger scale imposes more problems for SFS concerning details. The shadow region along the southern inside slope of the big impact crater exhibits errors as well. Further improvements may be expected in due course with methodical expansions and refinements of DRS.

Fig. 3a

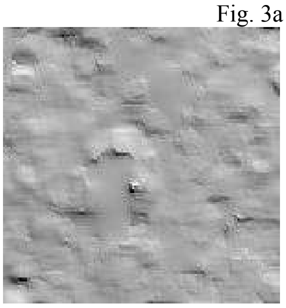

Fig. 3b

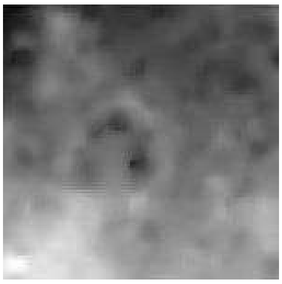

Fig. 3c

Fig. 3b,c,d:
Scene radiance, DEM image and contour map prior to SFS

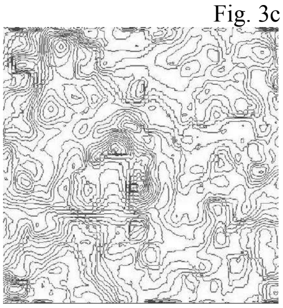

Fig. 3d

Fig. 3e

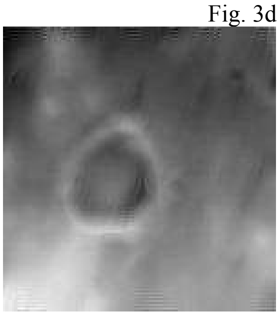

Fig. 3f

Fig. 3e,f,g:
Scene radiance, DEM image and contour map after SFS-refinement

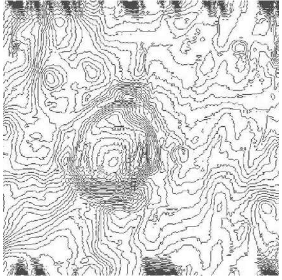

Fig. 3g

Figure 3. HRSC narrow-angle scene 15km by 15km at printing scale 1:400’000

4. CONCLUSIONS

The main objective of our DRS investigations is optimisation and homogenisation for relief shading of Mars image maps derived from HRSC data. So far the presented results are the outcome of our first yet most important development, viz. fine-tuned shape from shading modelling of the Martian surface DEM derived from elsewhere. Inspite of the still rudimentary and simplified stage of our studies, the results confirm the considerable refinement potential of SFS for an approximate DEM. In particular, after future removal of the main deficiencies in our approach, e.g., failure to comply with shadow extraction, space-variant stochastic elevation model, partial space-variant albedo, a further stabilization and improvement for the DEM may be expected.

The refined DEM can then be exposed to artificial illumination for the purpose of obtaining uniform relief shading of mosaicked ortho-images. For small scale MOC imagery this may already be done now. E.g., the MOC scene in Fig. 2 is shown again in Fig. 4, viz. as scene radiance derived from the SFS-refined DEM (Fig. 2e) with different illumination directions. Fig. 4a represents the surface under illumination from south-west, Fig. 4b from north-east. Note the relief inversion in Fig. 4a, an effect that has to be avoided by all means (optimisation of relief shading).

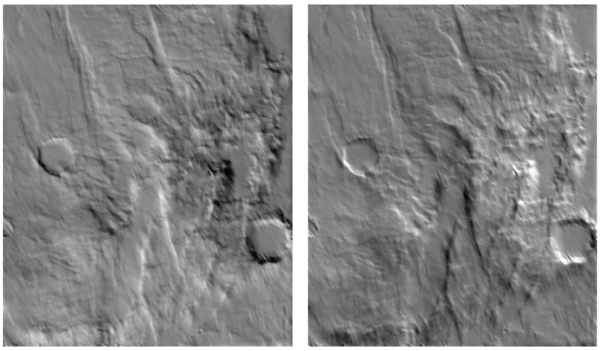

Fig. 4a Fig. 4b

Figure 4. Artificial relief shading of MOC scene

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