INVESTIGATING FLUVIAL TOPOGRAPHY FORMING PROCESSES OF THE MARTIAN SURFACE BY MEANS OF RASTER BASED GEOMETRY ANALYSIS

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ABSTRACT:

Recent Mars missions like ESA's Mars Express (MEX) and NASA's Mars Global Surveyor (MGS) capture the Martian surface at high resolution and in 3D. For instance, the MEX instrument High Resolution Stereo Camera (HRSC) acquires images at a resolution of up to 12m per pixel. Area based image matching within stereo pairs of HRSC images can be used to determine numerous points of the Martian topography. The MGS instrument Mars Orbiter Laser Altimeter (MOLA) acquires surface points by range measurement. Sophisticated methods enable the derivation of DTMs from such datasets.

Currently, geological investigations regarding the Mars are mostly based on human driven interpretation of images (e.g. captured by HRSC/SRC on MEX, Mars Orbiter Camera (MOC) on MGS or THEMIS on Mars Odysee), photometry analysis (e.g. HRSC), and measurements and 3D analysis of stereo pairs of images. If Digital Terrain Models (DTMs) are considered (e.g. HRSC, MOLA), their interpretation often is reduced to the analysis of profiles derived thereof. Overall analysis of DTMs is rarely performed.

Raster based geometry analysis allows fast, efficient and automatic mathematical analysis of terrain models (e.g. computation of curvature, exposition or slope). Hydrological analysis methods such as the detection of depressions, potential river lines and watersheds, or the derivation of catchment areas are predestined to be realized in a raster based manner, as well. In this paper, an approach for the implementation of hydrological analysis methods as systolic processes (i.e. the conditions of the cells of a DTM are derived synchronously) is described. The visualization of the results is prepared by means of special filtering operations. Exemplary applications on high resolution DTMs derived from HRSC images and comparisons to low resolution models derived from MOLA points, are presented and discussed. Their applicability for geological analysis is stressed, as well.

1. INTRODUCTION

The High Resolution Stereo Camera (HRSC, Neukum et al., 2004) on board of the European space craft Mars Express (MEX) has been providing stereo images of the Martian surface since early 2004. From these images, 3D object points are derived by area based matching at the German Aerospace Center (DLR). Based on these points, Digital Terrain Models (DTMs) with a resolution of 200m (sinusoidal projection based on the mean meridian of the respective orbit) are derived thereof by means of standardized methods (Scholten et al., 2005). DTMs with higher resolution (up to 25m, depending on the resolution of the images and the local albedo features) are generated by members of the HRSC on MEX *Photogrammetry and Cartography Working Group*. Results are compared in the HRSC DTM Test (Heipke et al., 2006).

The methods presented in this article, were applied to high resolution DTMs derived from HRSC data. The models were computed within a cooperation of DLR (Gwinner et al., 2005), who realized a sophisticated image matching approach, and Vienna University of Technology (Attwenger et al., 2005), who applied point classification methods on the matching data and derived the final DTMs.

For verification purposes, the Mars-wide available grid DTM (resolution of some 460m in equatorial regions) derived from Mars Orbiter Laser Altimeter (MOLA) data was used additionally. The laser profiling altimeter MOLA aboard Mars Global Surveyor (MGS) acquired more than 600 million single points along the ground track of the orbiter in the period 1997 – 2001 (Neumann et al., 2006).

Geological analysis methods commonly used for investigating the Martian terrain are

- visual interpretation of images (e.g. HRSC and Super Resolution Channel of MEX, Mars Orbiter Camera (MOC) of MGS, THEMIS of Mars Odysee, …),
- photometry analysis (e.g. HRSC),
- measurements and 3D analysis of stereo pairs of images (e.g. HRSC, MOC), and
- analysis of MOLA tracks and profiles derived from HRSC DTMs.

Unfortunately, such approaches provide only local, partly subjective impressions and data processing cannot be automated easily. Therefore, lots of information provided by

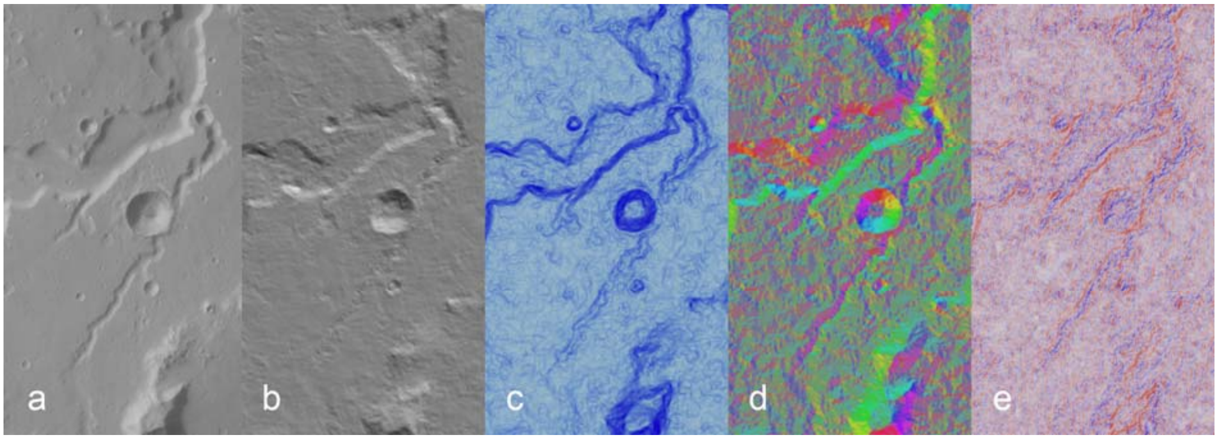

Figure 1: a) Cut-out of the HRSC nadir image of orbit 905 (Nanedi Valles), b) shaded relief of the corresponding high resolution (50m) HRSC DTM, c) – e) raster based analysis by means of this DTM: c) slope model, d) exposition model, e) curvature model.

DTMs implicitly is neglected, which might be useful information for geological investigations. Furthermore, digital models are predestined for spacious and automatic analysis by applying appropriate methods.

A more sophisticated approach for valley network analysis was developed by Lou and Howard (2005). T.F. Stepinski and A.F. Stepinski (2005) investigate drainage basins. Both groups apply circularity functions on DTMs.

The advantages of raster based analysis methods are their capability for fully automatically application to large areas and their prior objectivity, independent of human interpretation. In this article, two groups of raster based methods are discussed: mathematical and hydrological ones.

After a short discussion of the application of mathematical raster based methods, the concept of hydrological raster based analysis methods is introduced in the following section 2. Such methods were already implemented at the Institute of Photogrammetry and Remote Sensing in the early 1990s (Rieger, 1992) and were subsequently improved by Gajski (2000). Their application on MOLA DTMs was presented by Dorninger et al. (2004). For this, a couple of filtering operations have been tested in order to increase the usability of the results for further geological and hydrological interpretation. In section 3 results of processing high resolution Mars DTMs are compared to low resolution ones. The achievable quality is shown and the results are discussed. The paper ends with conclusions and an outlook on further improvements of the method.

2. RASTER BASED ANALYSIS METHODS

The raster based analysis methods discussed in the following are implemented as systolic processes. Thus, the conditions of the cells in the given grid array are derived synchronously by taking only their neighbors into consideration. The visualization of the results is prepared with the help of special filtering operations.

2.1 Mathematical methods

Mathematical raster based analysis methods based on DTMs are the derivation of slope, curvature and exposition models. They enable spacious and objective impressions on the Martian surface.

In Figure 1 an example derived on the basis of an HRSC DTM with a resolution of 50m is shown. Shaded reliefs are commonly used for DTM visualization. Unfortunately, they are dependent on azimuth and zenith distance of the artificial light source. The interpretability of color coded height visualizations strongly depends on the color table used and on the definition of the height intervals. On the contrary, visualizations of mathematical analysis methods (e.g. slope, curvature and exposition models) give an objective impression of the surface and do not suffer from these deficiencies. In the southern part of Figure 1 this can be seen clearly concentrating on the trench from south-west to north-east. In the HRSC nadir image (a) the trench is visible clearly, but in the shaded relief (illumination direction: north) of the DTM (b) it is hardly discernable. Within the slope, exposition and curvature models (c - e) it can be detected easily. Additionally, curvature models can be used to derive roughness maps of the surface.

2.2 Hydrological analysis

According to the current standard of knowledge, the formation of large areas of the current Mars topography has been influenced by fluvial processes. Therefore, hydrological analysis has a high potential to support the derivation of models, which can be applied to model the behavior of possible former surface water (or other flowing material) on Mars in a plausible manner. Such raster based methods provide useful additional information for geological analysis. An artificial rain simulation can be described as follows:

First, a so-called "rain layer" has to be defined, representing the amount of water brought onto every DTM element during every iteration step of the simulated rainfall. This layer can be constant or it might change through time. In principle, the surface itself is considered to be impermeable, although it is possible to model the permeability of the surface by means of a changing "rain layer". During the rainfall simulation, the adequate amount of water is brought onto every DTM cell.

Depending on the height of its neighborhood, the water drains in a certain direction; the steeper the area, the faster the drainage (only the full neighbors (4-environment) are considered). The amount of water is permitted to be split up to several neighbor cells. After having left the surface element, a new amount of water is brought in. These two steps are repeated iteratively, until a predefined breaking condition is reached (e.g. a number of iterations or a final condition of equilibrium). During this process, rivers will emerge as soon as there is enough water available flowing from the adjacent slopes to the riverbed. These rivers start to make their way downwards following gravity (assuming orthometric heights). If a river flows into a local minimum, as it occurs, for instance, in a crater, it starts to flood this minimum, until its lowest border point (at the crater rim) is reached. The resulting flooded area defines a local minimum with no way out other than the outflow point. It can be interpreted as a lake. From then on, the river follows gravity again, until it reaches the border of the defined area of interest where the water flows out.

The above described behavior is realized in two steps:

1. *Depression analysis* to find local minima, the corresponding outflow points and the extensions of the lakes, emerging in the surroundings of the minima, filling them up to their outflow points. Thus, depth and extension of the depressions are derived as meta-information and can be used for subsequent classification (e.g. to suppress very shallow or small pits, which are likely to be caused by DTM insufficiencies).

2. *Drainage analysis* representing the amount of water as a 2D array of values after reaching the condition of equilibrium or any other breaking condition. Hence, further analysis may be appended such as the derivation of river lines and watersheds.

For further scientific investigation, it is necessary to visualize the results. For instance, an overlay of rivers and lakes provides a realistic visualization of water behavior on an impermeable surface during permanent, homogeneous rainfall. For interpretation purposes, filtering operations (i.e. digital image processing) have turned out to be useful. The complexity of the river line and watershed model can be influenced by defining a minimum length of river branches and the minimum area of the corresponding catchment areas.

3. HYDROLOGICAL ANALYSIS OF THE MARTIAN TOPOGRAPHY

As investigation area, a rather flat terrain with a size of approximately 19000km² within the *Nanedi Valles* was chosen. The methods were applied to a high resolution DTM (grid width: 50m) derived from HRSC data (cut-out of a mosaic of the orbits 894, 905 and 927). The results were compared to a MOLA grid DTM (grid width: 1/128° = ~463m). Figure 2 shows visualizations of the results (left: HRSC, right: MOLA). (a) and (d) are shaded relief visualizations of the original DTMs. (b) and (e) show the result of the depression analysis (light blue) superimposed on the shaded relieves. In (c) and (f), the detected river lines (dark blue) are visualized additionally. (d) and (g) show color coded visualizations of the surface drainage behavior, the so-called drainage model, after the iteratively applied rain simulation.

In the following, the advantages and deficiencies of DTMs with different resolution are discussed considering their applicability for the interpretation of the results of the previously described hydrological methods.

3.1 Application on high resolution HRSC DTMs

3.1.1 Depression Analysis

Applying the depression analysis on an HRSC DTM (Figure 2 (b)) makes all craters discernable as they represent local minima within the surrounding terrain. On the contrary, the very flat area in the north-east appears as a great depression, as well. The most interesting fact is that the big trenches within the *Nanedi Valles* network are detected as depressions, too. Thus, a small amount of water would not flow through these trenches, considering the current surface topography of Mars. With a great effort, this might be detected by (numerous) profiles or using a height coding ideal for this special feature, as well. Obviously, this would require a huge amount of human interaction.

The figure shows all depressions detected within the DTM including those, occurring due to small unevenness within the terrain model or caused by DTM deficiencies. As already mentioned, these artifacts might be either eliminated using additional information (e.g. size, depth) or be by means of morphological filtering methods.

3.1.2 River Detection and Drainage Analysis

A vector based visualization of the way water would flow down from highlands to the depressions is shown in (c). The described method allows to define the complexity of the resulting river network by two parameters: The minimum catchment area of the river segments (in this case: 5km²) and the minimum length of river branches to be accepted (in this case: 1km). Applying smaller values increases the complexity of the resulting river and watershed network enormously. Such results might be used for large scale investigations but not for an overview as it presented in Figure 2.

The drainage model shown in (d) as a color coded visualization gives information on the occurring amount of water on each grid cell at a certain time (In this case: after the final iteration = condition of equilibrium). The possibility of backwater is not considered. Darker colors represent a greater amount of water. For reasons of better visibility within this paper, the drainage model was reduced to a grid width of 200m.

3.2 Application on MOLA DTMs

3.2.1 Depression Analysis

Due to the lower resolution and the high inner accuracy of neighboring grid points of the MOLA DTM, fewer depressions are detected. The result is shown in (f). Spacious features such as the great craters in the investigation area are detected correctly. Within the trench again depressions are detected, but they appear much greater and continuous compared to the HRSC result. Due to the data distribution of MOLA tracks (across track distances of partly several thousand meters), thin and drawn-out features are not modeled correctly within the DTM. This has to be considered analyzing the MOLA DTMs. For large scale investigations compared to the above described HRSC results, the MOLA DTM has huge shortcomings.

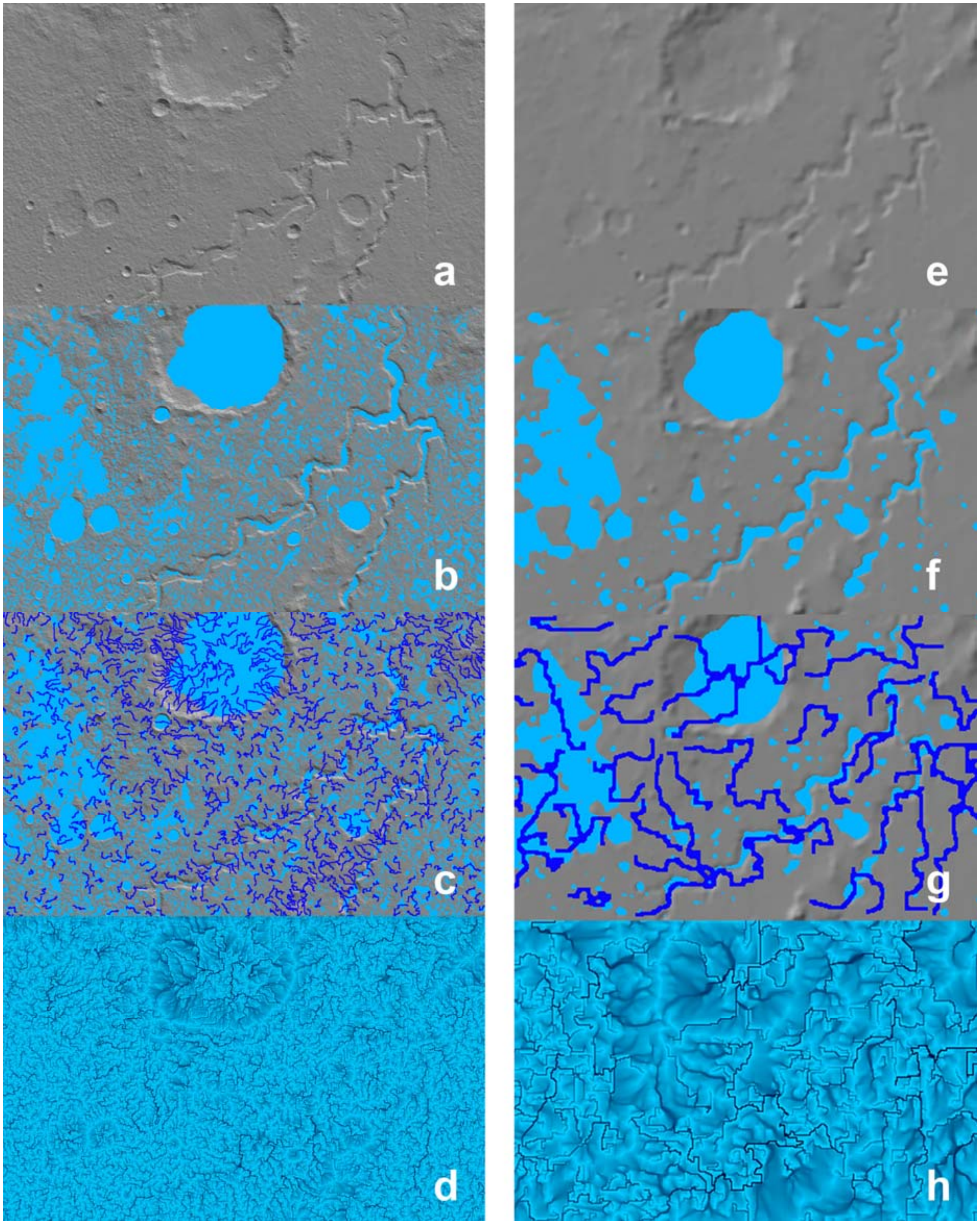

Figure 2: Comparison of raster based hydrological analysis applied to a high resolution HRSC DTM (left) and a MOLA DTM (right).

a) shaded relief of a high resolution (50m) HRSC DTM, b) – d) hydrological analyses based on this DTM;

e) shaded relief of a MOLA DTM, f) – h) hydrological analyses of this DTM;

b) and f) depression analysis, c) and g) depression analysis with superimposed river lines, d) and h) drainage model.

3.2.2 Rivers and Drainage

Analysing the MOLA DTM, the minimum length of river branches was defined with 25km and the minimum size of catchment area was set to 5km². The results of the river detection (g) and the drainage model (h) only show the great potential water flow. Local surface behaviour is not considered.

3.3 Remarks on the resolution of DTMs

Considering the different terrain models available from the Martian surface, the following question arises: Are there prerequisites for the input DTM used for raster based, hydrological analysis concerning DTM resolution and DTM computation?

The resolution of the input DTM depends mainly on the minimum size of geological features to be analyzed, thus influencing the achievable scale of the output. Therefore, applying raster based, hydrological analysis to MOLA DTMs is useful to analyze small scale surface behavior. Nevertheless, the inhomogeneous data distribution of the original MOLA track points influences the results. Dependent on the occurring surface albedo features, the HRSC points are characterized by a more homogeneous distribution. Investigations of high resolution HRSC DTMs give detailed insight into the Martian terrain characteristics. In any case, the size of the minimum catchment area and minimum the length of the rivers play an important role and have to be adapted to the DTM grid.

4. CONCLUSIONS AND OUTLOOK

Results of raster based analysis methods can provide a good insight to the characteristic of the Martian terrain. They can be used to get a fast impression of the surface topography and thus, to find regions, where further, detailed geological analysis might be reasonable. The described mathematical approaches enable a more objective interpretation of the surface as compared to shaded relief or color coded height visualizations.

Hydrological methods give insight to a potential surface water behavior. Local depressions can be detected and subsequently analyzed (size, depth, volume, …) by applying the described depression analysis methods. The computation of a drainage model can be used to analyze the surface water behavior during a simulated rainfall. Thus, many geological questions might be answered using such models: Which areas might be flooded? Where comes the water from and where does it flow off? How much water flows down to a certain area?

HRSC DTMs are well suited for large scale investigations. The local topography can be analyzed in an appropriate way. Small craters can be determined easily (diameter: some 100m) and local surface structures (e.g. rims, valleys, …) can be detected clearly. The analysis of the rather low resolution MOLA DTMs seems to be reasonable for small scales only. Nevertheless, if available, HRSC DTMs are preferable for this application (possibly using an enlarged grid width). The main factors to be considered for deciding the DTM resolution to be analyzed are the minimum size of features to be taken into account and, unfortunately, the size of available computation memory due to the fact that the status of all cells is computed simultaneously.

Currently, the capabilities of the raster based hydrological algorithms are increased in order to allow a more complex description of the surface water behavior. For instance, the infiltration of water into the soil shall be considered (e.g. applying different infiltration parameters for different soils within the area of investigation). This can be realized by a dynamic rain layer as described in section 2. The capabilities of the depression detection are increased, as well. The described object oriented approach (i.e. each depression can be treated individually) enables a classification according to the meta-information (e.g. depth, volume or extension) provided for each pit. A higher resolution of the input DTM increases the number of input cells to be considered for the same area of the Martian surface. Thus, the data modeling methods become more complicated and the amount of input data increases. Therefore, the size of an area, which can be investigated within one step, decreases as the number of grid cells, which can be handled by the computer in one step, is restricted. Thus, concepts for splitting the area of interest into (probably overlapping) tiles are investigated, as well. Certainly, a simple, rectangular tiling might not be sufficient and a more complex approach (e.g. tiling along watersheds) has to be realized.

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