# VERY HIGH RESOLUTION STEREO DTM EXTRACTION AND ITS APPLICATION TO SURACE ROUGHNESS ESTIMATION OVER MARTIAN SURFACE


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**ABSTRACT:**

We have developed a processing workflow to extract very high resolution DTMs up to 0.5-4m grid-spacing from HiRise (Kim and Muller, 2007) and 12-18m gridded DTMs from CTX stereo pairs. This workflow relies on combining these data with the outputs of the UCL HRSC stereo processor, which is capable of producing 30-100m DTMs. This provides a unique capability to observe Martian topography at multiple resolutions. One of the most interesting applications for these data sets is local surface roughness extraction. An iterative method is employed to try to reduce noise in DTM extraction and applied to reconstruct surface roughness data, fusing stereo DTM and MOLA beam broadening effects. Accurate local surface roughness over a wide area will give important clues about the composition and origin of the Martian surface which has not been revealed before with methods developed to date.


## 1. INTRODUCTION

The local surface roughness is a very interesting and important property of planetary surfaces. It defines how momentum is transported from the atmosphere to the surface through the aerodynamic surface roughness length, Zo (Muller et al., 2001); how dust is raised into the atmosphere and for rock and boulder-strewn landscapes how their distributions came about due to events such as impact cratering and other explosive events. The vertical and horizontal resolution of conventional topographic data extraction methods such as stereo analysis have been severely limited in the past to extract this valuable information. An alternative for planetary surfaces, albeit only for along-track footprints, is through the use of laser altimeters. The relationship between laser beam pulse spreading and local surface roughness was first defined by Gardner (1982). Laser beam broadening was first demonstrated for Shuttle Laser Altimeter (SLA-01/2, Harding et al., 1994) and the Mars Orbiter Laser Altimeter (Abshire et al., 2000). On the other hand, local surface roughness extraction directly from height measurements has also been tested. The power spectrum method (Smith et al., 2001) and the median differential slope method (Kreslavsky and Head., 2000) to extract km scale surface roughness are good examples. However, in both cases, the vertical resolution is largely dependent on the horizontal density of MOLA spots which are limited to km scale. This is of less interest to surfaces such as Mars. Garvin et al., (1999) first demonstrated metre resolution Martian surface vertical roughness from the MOLA beam broadening effect. Then Smith et al., (2001) analysed the local roughness using MOLA beam broadening at the global scale and finally Neumann et al., (2003) extracted the local roughness at ¼ of a degree resolution from improved pulse characteristics. However, all of their studies have problems to apply surface slope correction. For example, Garvin et al., (1999) used the along track slope extracted from the footprint-to-footprint height differences and Neumann et al. (2003) employed a 1/64º gridded MOLA DTM. In both cases, these very crude slopes cannot effectively remove slope effects within the laser beam footprint as the footprint-to-footprint distance (320m) and the projected footprint (≈150m) is too coarse to characterise the within-footprint slope distribution.

A new solution to this problem is proposed here to employ multi-scale stereo DTMs. In this research, we show how effectively stereo DTMs extracted from different data sources can be combined with MOLA laser beam properties to calculate a more reliable and precise local surface roughness.

## 2. ALGORITHMS

### 2.1 High resolution stereo DTM extraction

Considering the MOLA footprint size (150m) and across track distance (>> 1km near the equator), it is clear that the horizontal resolution of MOLA data is not enough to provide details on key geomophological features. Therefore, stereo image analysis is still important even though it has relatively poor vertical accuracy (≈IFoV). Stereo image coverage of the Martian surface has dramatically increased since the successful orbital insertion of HRSC onboard ESA's Mars Express. Recently, the stereo image coverage of HRSC (≤20m) is up to 45.7% of Martian surface (Jaumann, 2008). One of the biggest attractions of HRSC stereo imagery is that it's positional accuracy is well co-registered with MOLA. As a result, a HRSC pixel has an inherent planimetric accuracy of 25-40m and a 3D space intersection of up to 6-8m vertical registration with MOLA, if the improved exterior and interior orientation from bundle adjustment is employed (Speigel, 2007). This means that the HRSC image and derived DTM can be employed as the base data for other optical image's geometric calibration. A barrier to this idea is the inherent difficulty in co-registration due to the resolution differences between HRSC and other high resolution (>few metre pixel resolution) imagery such as CTX or MOC-NA and very high resolution (<<1m resolution) imagery such as HiRISE. Our solution, to address this problem, has been to employ a hierarchical co-registration between different resolution imagery or re-sampled images. For example, in one area, which includes coverage by HRSC, CTX and HiRISE stereo images, the HRSC intersection points and orthorectified images (ORIs) provide the first geodetic control information for the CTX imagery because the registration between CTX and HRSC is not so difficult (a factor of ≈2-3 difference in


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resolution). Then processed CTX DTMS and ORIs based on HRSC photogrammetic data can be employed as the source of the geodetic control for <<1m HiRISE stereo images. Considering the significant resolution differences between CTX and HiRISE (a factor of ≈30), the registration is performed hierachically between CTX products and resampled HiRISE images of up to 3-4 metres resolution and then the intersection points and ORIs of the resampled HiRISE are feed-forwarded into the next finest resolution. The fact that CTX and HiRISE data are acquired simultaneously on the same platform also helps considerably. Such processing reduced the possibility of the wrong co-registration being accidentally found and gradually improves the positioning accuracy of the topographic products by the triangulation process at each stage.

The other important approach in our work is the employment of non-rigorous sensor models which was first introduced by Kim and Muller (2006). These sensor modelling methods provide an unified method to be applied with different sensors and can readily be incorporated into our geodetic control strategy.

The ideal scenario of stereo processing is to employ HRSC – CTX – HiRISE multi-resolution chains but the number of cases that a target area includes all three stereo image sources is relatively rare. A more direct registration between HRSC and HiRISE or MOLA and HiRISE was also attempted. Then, it was shown that this approach can be successful if the base data has an acceptable positional quality and resolution even though the photogrammetric accuracies of these products are not comparable with the ones processed using the stereo HRSC-CTX-HiRISE chain. The detailed photogrammetric accuracy check of our stereo processing line is treated in a separate study in depth (Kim & Muller, PSS, in preparation).

#### 2.1.1 HRSC DTM extraction

HRSC stereo DTMs are a very important source of global topographic slope data as well as geodetic information in this study. Since the accuracy of the extracted local surface roughness and other data's photogrammetric quality are largely dependent on HRSC DTM quality, a processing scheme to produce relative noise free intersection point clouds has been developed. In our stereo scheme, a two stage image matching system was employed. A front end image matcher based on Zitnick and Kanade (2000) algorithm generated high density seed points for ALSC (Adaptive Least Squares Correlation) refinement. The subsequent 3D intersection points from this matching scheme and the HRSC sensor model are compared with MOLA to remove significant outliers by slope analysis. Then the median filtered values at 50m resolution, which is around one-third of the size of MOLA footprint, are extracted. Such a processing method provides a natural sloped height surface so that the calculated local roughness values based on this DTM are relatively free from the influence of any height outliers and uncorrelated with slope. The resolution limit of a re-constructed DTM by this processing chain is actually around 25m with 12.5m original image resolution if the stereo image quality is relatively noise free. However, for the geodetic control of other stereo imagery, the most reliable intersection values in each matching position are chosen as the GCPs for other image's geodetic control. Then reliable control information at 12.5m resolution can be achieved.

#### 2.1.2 HiRISE DTM extraction

Currently, the most common stereo coverage of Martian surface is HRSC imagery. However the quality of reconstructed 3D Martian surfaces from HRSC stereo pair with 12.5 m spatial resolution is still not appropriate for some geological applications. For example, for direct surface roughness extraction. The successful deployment of the NASA MRO with the 25cm HiRISE instrument provides an opportunity to address this issue for up to 1% of the Martian surface. One of the difficulties in fully exploiting the potential of HiRISE for photogrammetric products is that there are some technical issues to use the tracking information for sensor modelling (Kirk et al., 2007). Therefore we have developed a simple workaround mapping method for HIRISE imagery using the strategy which is described here. This appears to produce very reasonable quality sets of mapping products including 0.5-4m resolution stereo DTMs and 25cm ORIs over various HiRISE stereo observation areas. If there is no CTX coverage, to enable precise registration between 12.5m resolution HRSC and 25cm HiRISE image, the scheme was constructed using a hierarchical processing chain and by combining an efficient image matcher which exploits both epi-polarity and ALSC (adaptive Least Squares Correlation; Gruen, 1985) refinement methods at each stage. Also the image matching noise and sensor characteristics are effectively removed by a multi stage iterative surface matching method. Therefore, this method can produce DTMs with a resolution from 0.5-4m according to the processing stage.

#### 2.1.3 CTX stereo DTM extraction

CTX stereo DTM has only been discussed in one short report on the NASA Ames stereo pipeline (Broxton and Edward, 2008). We have shown that our geodetic control method works well with CTX stereo images and produces DTMs which have 12-18m resolution. The stereo coverage of CTX is not yet as good as the HRSC stereo coverage but compared with HIRISE, it provides the higher resolution DTM availability at a reasonable resolution. The other importance of CTX stereo topographic data is its role to link between HRSC and HiRISE processing. We applied almost the same processing method as for HiRISE processing which is described here. It appears to produce good quality DTMs and ORIs probably because of the more stable sensor structure which employs one CCD line array rather than the complicated 24 CCD-TDI combination in HiRISE. Then the products of the CTX stereo chain are employed to produce geodetic control for HiRISE imagery.

### 2.2 MOLA data processing

Garder (1982) analysed the influence of various effects on the laser pulse width as follows

$$E(\sigma_{p^2}) = (\sigma_l{}^2 + \sigma_h{}^2) + \frac{4Var(\xi)\cos^2 S_{\mathrm{II}}}{c^2\cos^2(\phi + S_{\mathrm{II}})} + \tag{1}$$
$$\frac{4R_m{}^2}{c^2}\tan^2\theta_t(\tan^2\theta_t + \tan^2(\phi + S_{II}) + \frac{\tan^2 S_\perp \cos^2 S_{II}}{\cos^2(\phi + S_{II})})$$

where $\sigma_l$ is the rms laser pulse width, $\sigma_h$ is the rms width of the receiver impulse response, *Rm* is the range from the spacecraft to the illuminated spot, $S_{\mathrm{II}}$ is the surface slope parallel to nadir direction, $S_\perp$ is the surface slope to the nadir direction, $\vartheta_t$ is the nominal divergence angle, *c* is the light speed and $\varphi$ is the off nadir angle.

In equation (1), the first term represents a system effect, the second the influence of height undulation and the third term is the effect of slope. Usually the off nadir angle is almost zero and the nominal divergence angle is relatively small, so (1) can be simplified to

$$E(\sigma_{p^2}) = (\sigma_l^2 + \sigma_h^2) + \frac{4Var(h)}{c^2} + \frac{4R_m^2}{c^2}\tan^2\theta_t(\tan^2 S_{II} + \tan^2 S_{\perp}) \quad (2)$$

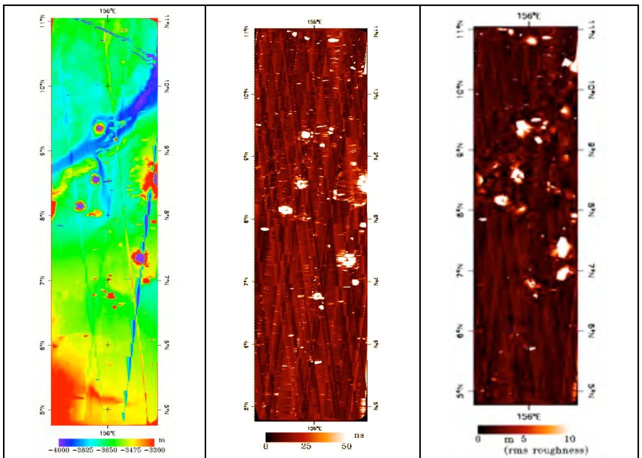
where *Var(h)* is the height variance.
Therefore the local surface roughness can be derived by applying correction terms as follows

$$roughness_{rms} = 0.5c\sqrt{\sigma_{corr}^2 - \frac{4R_m^2}{c^2}\tan^2\theta_t(\tan^2 S_{II} + \tan^2 S_{\perp})} \quad (3)$$

In (3), $\sigma_{corr}$ is the corrected pulse width which is recorded in the MOLA PEDR data record where correction refers to filter characteristics and threshold settings, as determined by the receiver model (one sigma value, with the minimum limited by the filter response; Neumann et al., 2003). The extracted $\sigma_{corr}$ value is corrected in two stages: (1) Removal of noisy tracks which is shown in Figure 1 a. compared with some noisy free reference planes such as HRSC DTMs; (b) slope correction by Eq (3). However the extracted $\sigma_{corr}$ values or local surface roughness even after noisy track removal and slope correction using MOLA height values which is corrected by crossover check (Neumann et al., 2001) revealed strong across track artefacts which can be observed in Figure 1 b) and c). The reason for these across track artifacts is that some of the vertical range errors within individual tracks were not corrected.
The height of the surface can be determined from the MOLA measurements and the spacecraft tracking information (Abshire et al., 2000) as

$$h_s = [R_{MGS}^2 + R_m^2 - 2R_m R_{MGS}\cos^2(\phi)]^2 - R_{ref} \quad (4)$$

where $R_{MGS}$ is the radius of the MGS spacecraft orbit, $R_{ref}$ is the radius of reference. The error in $R_{MGS}$ or possibly error of the off nadir angle produces a deviation from the surface and creates a false across-track slope effect.



| (a) height values using MOLA uncorrected planet radius | (b) The received pulse width after removing bad orbits | (c) local roughness after slope correction using 500m MOLA Gridded DTM |
|---|---|---|

Figure 1. The influence of noisy MOLA tracks on topographic height values, received pulse widths and local surface roughness

Now there is one more correction term in equation (3)

$$roughness_{rms} = 0.5c\sqrt{\sigma_{spigot}^2 - \frac{4R_m^2}{c^2}\tan^2\theta_t(\tan^2 S_{\perp uncorrt} + \tan^2 S_{II} + \tan^2 S_{\perp})} \quad (5)$$

where $S_{\perp uncorrt}$ is the false slope which is produced by some tracking information.

In this study, the slope correction procedure can be performed in two ways.
1) Apply a slope correction using the height differences between un-crossover corrected MOLA tracks and the MOLA Grid DTM.
2) Apply a slope correction in the along track and across direction using HRSC & CTX DTMs. The slope values are extracted using nearest height points in the across and along end side of individual MOLA footprints. This has the added advantage of correcting for a local slope error. One very important factor is the value of the nominal divergence angle. Abshire et al. (2000) stated this value as 93μrad. However, Neumann et al., (2003) used an approximation consisting of fitting 0.5 times the nominal angle from inflight data. The nominal divergence angle largely influences the amount of slope correction. We tried to find optimal values using saturations of the slope correction and height variation of HiRISE DTMs and found the optimal values as 33 μrad.

## 3. RESULTS AND ASSESSMENT

Our study site is in the Athabasca valley. The main channel of the Athabasca valley is covered by HRSC orbit 2099 and CTX stereo pair (P01_001540_1889 and P02__001804_1889). Part of the valley is covered by HiRISE stereo image pair (PSP_001540_1890 and PSP_002371_1890). First of all, various stereo DTMs were generated and then the correction term was applied to the MOLA beam pulse width. Finally, corrected MOLA local surface roughness tracks were compared with ortho images and the standard deviation of height values derived from the HiRISE DTM.

### 3.1 Stereo processing results

Over the central part of the Athabasca area, four different resolution DTMs were extracted (Figure 3). These consists of a 50m HRSC stereo DTM; 18m CTX stereo DTM; 3.5m HiRISE DTM for the whole HiRISE stereo area and a 70cm DTM over some selected area.

Coarse resolution DTMs and ORIs were used for the geodetic control of the next stage as described in the previous section, so that registration between different DTMs and ORIs can be guaranteed so long as the non-rigorous sensor model is working. When the ORI products are superimposed from different products they appear to be seamlessly co-registered. This suggests that the geodetic control accuracy in this research is sufficient to allow completion of this analysis (Figure 2).

Close-up images over a few areas (Figure 3(b)-(f)) using different data resolutions, clearly show the kind of information which is available from individual DTM sources. For example 50m resolution HRSC usually show the general outline of the overall slope.

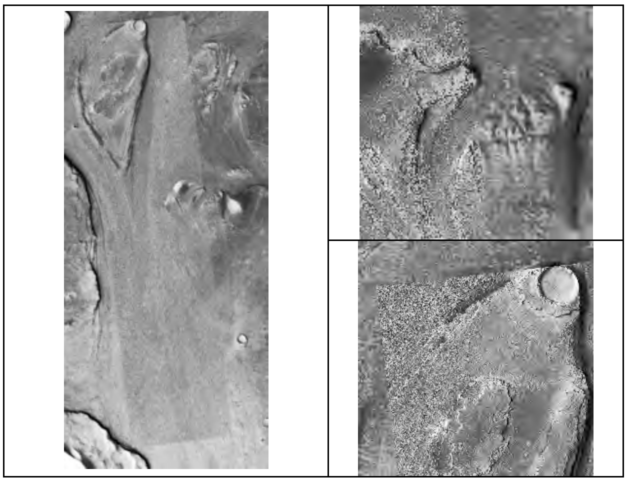
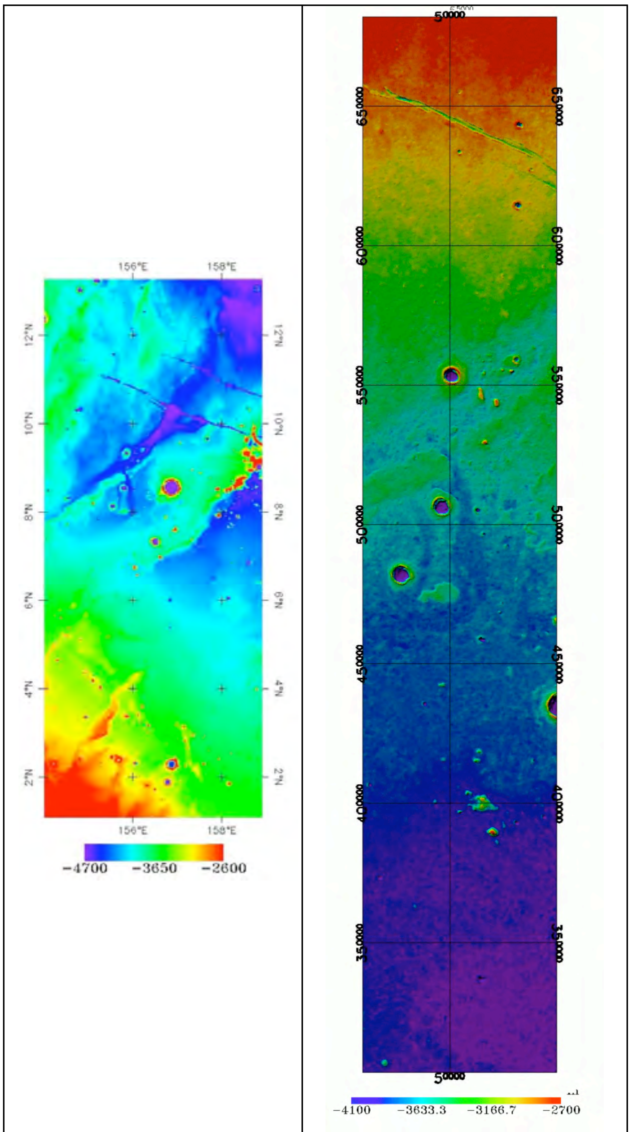
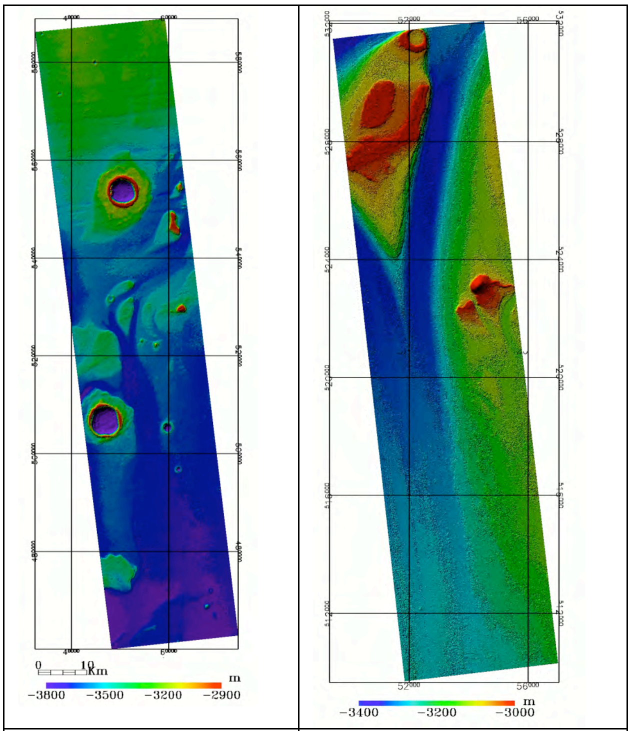


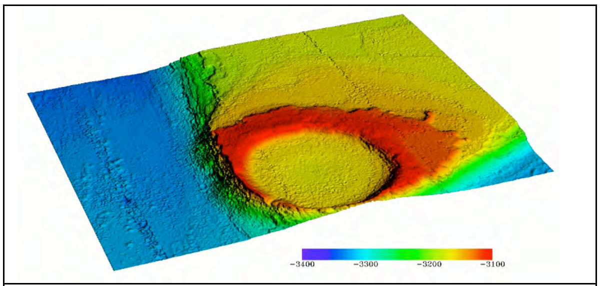
Figure 2. Geodetic co-registration check using orthoimage superimposition (left: CTX-HRSC; right:CTX-HiRISE)



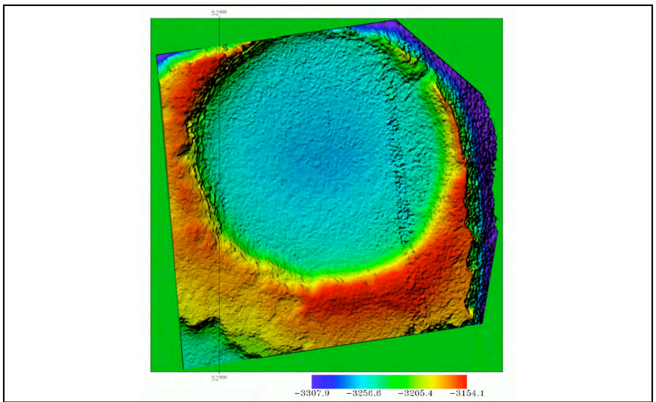

(a) 500m MOLA DTM | (b) 50m stereo HRSC DTM




(c) 18m CTX stereo DTM | (d) 3.5m HiRISE stereo DTN



(e) 1.5m HiRISE stereo DTM



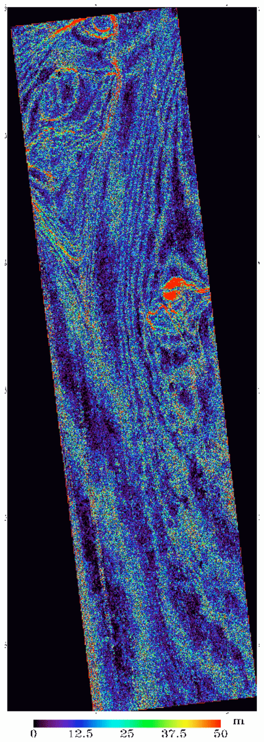
(e) 0.7m HiRISE stereo DTM

Figure 3. Multiresolution stereo DTMs compared with each other over the Athabasca area. Note the TDI array (e) which could not be corrected due to image noise.

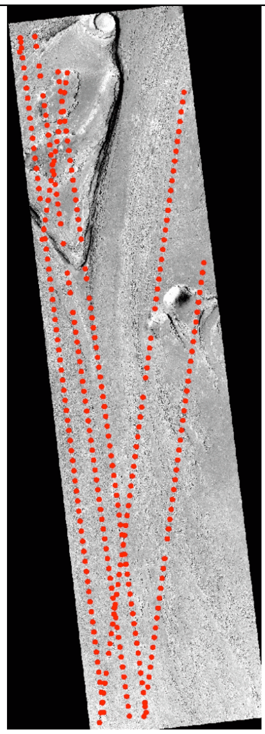
However, 18m CTX DTMs make it possible to depict the shape of an individual landscape feature such as a medium scale impact crater (radius > few hundreds of metres) or the shape of valley and streamline islands. 3.5 m resolution HiRISE DTM show finescale detail of very flat areas including surface roughness features. 70cm HiRISE DTMs provides a measurable sub-metre resolution vertical local roughness. This means that the height variation of the 70cm HiRISE DTM is directly comparable with the local surface roughness values from the MOLA laser beam broadening.

### 3.2 MOLA local surface roughness results

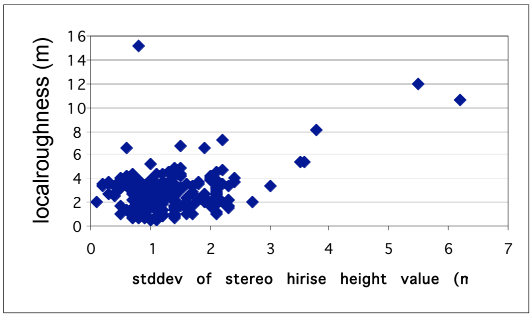
At first, we extracted the most reliable base height map using 1.5m resolution HiRISE DTMs from median filtered 3D intersection points. The new nominal divergence angle values were then fitted as shown in Figure 4 to minimise the differences between a slope corrected MOLA local roughness and the height variation of normalised HiRISE DTMs. These values are then used for the slope correction with MOLA, HRSC and CTX DTMs.




(a) HIRISE height variance above the best fitted MOLA surface height



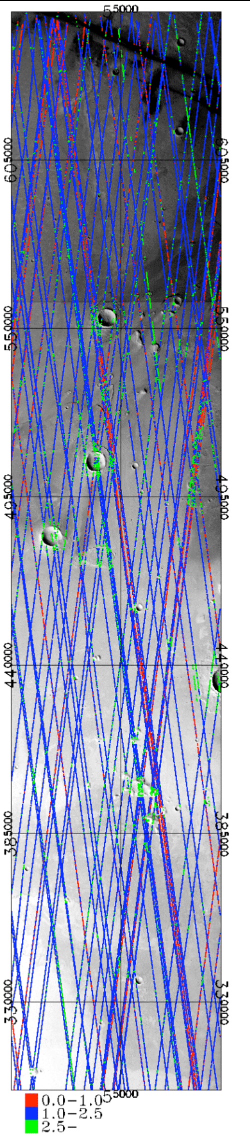
(b) MOLA track profiles over HiRISE stereo images



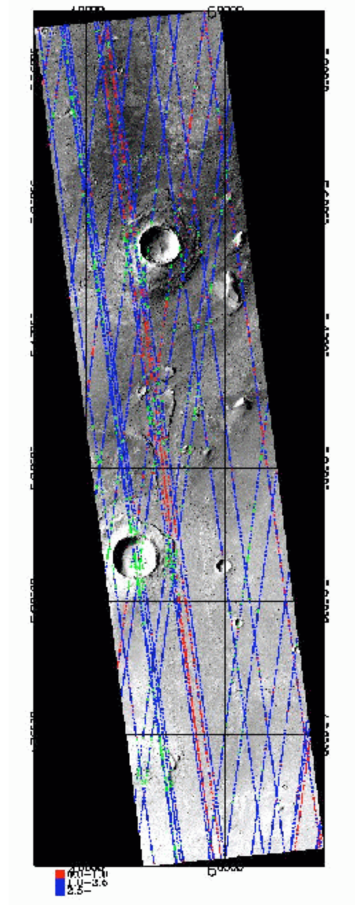

(c) local roughness extracted from MOLA beam broadening vs. standard deviation of **normalised** HiRISE height points within the corresponding MOLA footprint with nominal divergence angle=33 μ rad which shows the best correlation between two

Figure 4. HiRise-MOLA inter-comparison and the divergence angle fitted with a normalised (slope reduced) HiRISE DTM standard deviation of heights

The topic investigated in such analysis is the direct comparison of the numerical local surface roughness with the height deviation of the HiRISE DTM. Figure 4 shows that the local surface roughness value, corrected for the slope effects, is correlated to the real metre level height variation.




(a) corrected local surface roughness with 50m HSRC DTM



(b) corrected local roughness with 18m CTX DTM

Figure 5. The corrected RMS local roughness MOLA profiles

Even after applying slope correction using MOLA CTX and HRSC DTMs, the artifacts due to crossing tracks in the pulse beam broadening were not completely resolved (Figure 5). However, well corrected local surface roughness areas show the correlation with the surface geomorphology to a certain extent. As shown in Figure 5**,** local surface roughness in the MOLA track overlaid on an ORI image, shows obvious features.

## 4. CONCLUSIONS & FUTURE WORK

We extracted various resolution stereo DTMs from 50m up to 0.7m. All important geological and geomorphological observations including direct extraction of metre scale local height variations can be performed with such multi-resolution topographic data sets. However, the availability of such triplets of stereo images (HRSC, CTX and HIRISE) over the entire Martian surface is likely to remain pretty limited. One of the important surface properties, local surface roughness was extracted combining the MOLA beam broadening signature and 18-50m stereo DTMs which are available over a relatively wide area. Unfortunately, the influence of uncorrected MOLA height values remained in the across track artefacts so that an area local surface roughness analysis is not yet feasible. However, our study did partly show the correlation of surface roughness with the distribution of geological and geo-morphological features. With the individual track's MOLA local surface roughness across different origin's dichotomy, this correlation is relatively clear.

One issue that requires future solution is to make precise slope effect correction in local surface roughness by improving the accuracy of co-registration with MOLA data. The horizontal and vertical accuracies of HRSC shown by Speigel (2007) may not be enough to calculate very high accuracy slope correction values. Also, there is still some possibility of a few tens of metres shift between HRSC and other very high resolution topographic products such as HiRISE and CTX DTMs due to errors in orientation. To address this problem, over the basic approach demonstrated in this study, the following improvements in the stereo processing chain are under development and show encouraging results.

1) The surface orientation adjustment between HRSC and CTX, HiRISE intersection points to set control points is being tried. This may lead to greatly improved accuracy of the HiRISE CTX SPICE kernel pointing information. The updated SPICE kernel can be combined with our current non-rigorous model to decrease the error of some horizontal shift which is currently observed between HRSC and HiRISE mapping products. 2) A more sophisticated matching system employing sensor information and illumination is under development to attain maximum possible DTM resolution.

Such improvements should guarantee more noise free and photogrammetrically accurate mapping products so the more precise CTX and HiRISE DTM products will be applicable for surface roughness extraction purposes in the future.

In addition, a Lidar simulation using back ray-tracing methods (Muller & Dalton, 1989; Lewis, 1999) will be tried with the HiRISE DTMs to give better insights into how the slope effects can be corrected. Once the best possible correction term is known the method will be applied over wider areas using HRSC global DTMs. Finally those local surface roughness extraction procedures should provide the data sets for a much better understanding of Martian surface process and the future selection of landing sites.

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