Grant agreement no.607379

SPA.2013.2.1-01 - Analysis of Mars Multi-Resolution Images using Auto-Coregistration, Data Mining and Crowd Source Techniques

- Collaborative project –

D4.5

Validation of CTX and HiRISE DTMs

WP4 - Global DTM/ORI production & validation

Due date of deliverable: month 35 – November 2016

Actual submission date: 29th March 2017 *(*) EC approval pending*

Start date of project: 1st January 2014 Duration: 39 months

Lead beneficiary for this deliverable: UCL

Last editor: Jan-Peter Muller (UCL)

Contributors: Konrad Willner, Marita Wählisch, Klaus Gwinner (DLR), Jung-Rack Kim (UoS)

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

History table

Version	Date	Released by	Comments
V0.1	02.09.2016	Konrad Willner	First version
V0.2	16.12.2016	Konrad Willner	Second version
V0.3	13.03.2017	Klaus Gwinner	Third version
V0.9	20.03.2017	Jan-Peter Muller	Added HiRISE section
V1.0	28.03.2017	Jan-Peter Muller	Added Annex from UoS

Executive Summary

The iMars project focuses on developing tools and value-added datasets to increase the exploitation of space-based data from NASA and ESA mission imaging and 3D data beyond the instrument teams. iMars adds value by creating more complete and fused 3D models of the surface from combined stereo and laser altimetry and use these 3D models to create a set of co-registered imaging data through time, permitting a much more comprehensive interpretation of the Martian surface to be made. Emphasis is placed on co-registration of multiple datasets from different space agencies and orbiting platforms around Mars and their synergistic use to discover what surface changes have occurred since NASA's Viking Orbiter spacecraft in the mid-1970's.

The ESA Mars Express High Resolution Camera (HRSC) will provide the base data, where possible. The iMars base data can then be used by the ESA ExoMars Trace Gas Orbiter 2016 and subsequent ESA missions to provide the necessary inputs for selection of a future landing site for the ESA ExoMars 2020 rover and for any Mars Sample Return missions in the 2020s. iMars will greatly extend the use of archived data by providing mapped and co-registered images. The resultant time-stamped imagery is interfaced to automated data mining analysis software based on techniques developed for Earth surveillance.

This document reports about the validation process of the derived data products of iMars. Here the focus is given to the digital terrain model (DTM) products derived from the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) and HiRISE data and co-registered to the HRSC reference data. Products provided by the project partners MSSL/UCL and the University of Seoul (UoS) are validated. A summary of input data will be given followed by the approach how data products are validated. The report includes the validation record and judgement of quality with respect to co-registration and general quality – completeness, noise, visible systematic effects, etc. – is given. The self-validation by UoS of their CTX and HiRISE DTM products is described. The self-validation of the UCL CTX products is described in D4.2 using a visual quality grading system into 5 categories.

Table of Contents

List of Tables

List of Figures

Key word list

Martian surface mapping; remote sensing; digital terrain models; stereo-matching; image processing algorithms; image feature detection; georeferencing; image co-registration

Definitions and acronyms

Acronyms	Definitions
UCL	University College London
UoS	University of Seoul
WP4	Work Package Four
MSL	Mars Science Laboratory
MRO	Mars Reconnaissance Orbiter
CTX	Context Camera
HiRISE	High Resolution Imaging Science Experiment
MOLA	Mars Orbiter Laser Altimeter
HRSC	High Resolution Stereo Camera
ORI	Ortho-Rectified Image
MER	Mars Exploration Rover
DTM	Digital Terrain Model
SSW	South-South-West
NNE	North-North-East
VICAR	Video Image Communication and Retrieval

1 Introduction

Within the WP4 work package of the iMars project, the project partners UCL and UoS are responsible for the development of an automated processing chain for producing and co-registering data products like digital terrain models (DTM) or Ortho-Rectified Images (ORI) of the Context Camera (CTX) to derived data products of the High Resolution Stereo Camera (HRSC). Subsequently High Resolution Imaging Science Experiment (HiRISE) image data and products thereof are co-registered to CTX data to achieve a common reference between the three data sets. As a result all data sets of CTX and HiRISE can be considered to be co-registered to the MOLA data set as HRSC derived data are co-registered to MOLA (Gwinner et al., 2016; Gwinner et al., 2009). DLR has the task to independently validate the DTM products of these automated processing chains with respect to quality of resolved detail and quality of co-registration.

Since the Mars Orbiter Laser Altimeter (MOLA) data set provides the geodetic reference definition for the Martian surface that is accepted among the science community, all products of iMars shall be co-referenced with this data set. However, due to the wide range of resolution from several hundred meters in the MOLA dataset to sub-meter resolution in HiRISE data, co-registration is always validated against the next level of available resolution (cf. Table 1-1). E.g. HiRISE (30 cm per pixel resolution in ORI) co-registration cannot be validated directly with respect to the MOLA data but will be tested against a CTX (6 m per pixel resolution in ORI). CTX ortho-rectified images and derived data products will be validated against HRSC images and data products.

Table 1-1: Reference datasets and their properties.

Data set	Base Resolution	DTM Resolution
MOLA	80 m spot size (Neumann et al., 2003)	463 m per pixel (Smith et al., 2003)
HRSC	12.5 m per pixel (Jaumann et al., 2007)	50 m per pixel and lower (Gwinner et al., 2009)
CTX	6 m per pixel (Malin et al., 2007)	12- 18 m per pixel (Kim and Muller, 2009a)
HiRISE	0.25 m per pixel (McEwen et al., 2007)	0.75-1m per pixel and lower

2 Input information

2.1 Information to be validated

Several data sets were delivered by UCL and UoS concentrating on the two MER and the MSL rover landing and traverse areas. These differ in map projection parameters. For validation, the input data was not resampled, instead data to compare against was resampled to fit the provided projection parameters. Consult Table 2-1 for an overview of properties of the delivered data.

Data were delivered in GeoTIFF format and converted to VICAR format prior to validation. It has been reported, validated and documented before (as a part of DLR's contribution to iMars WP 1) that this routine works according to defined standards of GeoTiFF and VICAR and no change in geometry and / or geo-reference occurs.

Table 2-1: Properties of CTX data delivered for validation.

Provider: / Data Type	UCL	UoS	Validated UCL/ UoS
MER-A			
DTM based on Resolution Centre longitude Reference Radius Height Reference Radius Map	CTX 18 m/pixel 176° 3396.00 km 3396.19 km	CTX 24 m/pixel 175° 3396.00 km 3396.00 km	yes /yes
ORI Resolution Centre longitude Reference Radius Map	CTX 6 m/pixel 176° 3396.19 km 3396.19 km	CTX 6 m/pixel 175° 3396.00 km 3396.00 km	no/no
MER-B			
DTM based on Resolution Centre longitude Reference Radius Height Reference Radius Map	CTX 18 m/pixel 354° 3396.00 km 3396.00 km	CTX 24 m/pixel 354° 3396.00 km 3396.00 km	yes /yes
ORI Resolution Centre longitude Reference Radius Map	CTX 6 m/pixel 354° 3396.00 km 3396.00 km	No delivery	no/no
MSL			
DTM based on Resolution Centre longitude Reference Radius Height Reference Radius Map	CTX 18 m/pixel 138° 3396.00 km 3396.00 km	CTX 24 m/pixel 137° 3396.00 km 3396.00 km	yes/yes
ORI Resolution Centre longitude Reference Radius Map	CTX 6 m/pixel 138° 3396.00 km 3396.00 km	No delivery	no/no

Table 2-2 Properties of HiRISE data delivered for validation.

Provider: / Data Type	UCL	Validated UCL
MER-A		
DTM based on Resolution Centre longitude Reference Radius Height Reference Radius Map	HiRISE 0.75 m/pixel 176° 3396.00 km 3396.19 km	yes /yes
ORI Resolution Centre longitude Reference Radius Map	HiRISE 0.25 m/pixel 176° 3396.19 km 3396.19 km	no/no

MER-B		
DTM based on Resolution Centre longitude Reference Radius Height Reference Radius Map	HiRISE 1 m/pixel 354° 3396.00 km 3396.00 km	yes /yes
ORI Resolution Centre longitude Reference Radius Map	HiRISE 0.5 m/pixel 354° 3396.00 km 3396.00 km	no/no
MSL		
DTM based on Resolution Centre longitude Reference Radius Height Reference Radius Map	HiRISE 0.75 m/pixel 138° 3396.00 km 3396.00 km	yes/yes
ORI Resolution Centre longitude Reference Radius Map	HiRISE 0.25 m/pixel 138° 3396.00 km 3396.00 km	no/no

2.2 *Information to validate against*

The CTX data were validated against HRSC level 4 data products. The HiRISE were validated against the validated CTX DTMs. Other data sets like MOLA are subject to significant restrictions concerning their use as validation datasets due to large resolution difference (cf. Table 1-1). CTX images have a spatial resolution of approximately 6 metres per pixel. The delivered DTM products result in gridded data of 18 to 24 metres per pixel resolution. In contrast, the MOLA spot size is known to be on the order of 80 metre diameter (Neumann et al., 2003) resulting in a gridded DTM of 463 metres per pixel resolution and thus not suitable for direct comparison with the CTX DTM data delivered.

The landing sites are covered by several HRSC observations. However these do differ in resolution and coverage. Table 2-3 provides a list of DTM data sets that were used for the validation.

Table 2-3: Overview HRSC data sets for the rover landing sites and traverse areas

Site	HRSC Data	Resolution	Coverage of CTX & HiRISE scenes
MER-A	h4165_0000.dt4.50	75 m/ pixel	Completely
MER-B	h1183_0000.dt4.53	100 m/ pixel	Completely
MSL	H4235_0001.dt4.50	50 m/ pixel	Completely

3 Validation Approach

Several tests were made to validate the provided data. The tests are comparable to methods applied by (Heipke et al., 2007). Though the template data are here the HRSC derived products and CTX derived products are compared to these and subsequently HiRISE compared to CTX. Also, as the test areas are the rover landing site areas only small numbers of craters can be found in the data. This limits the ability to validate the effective resolution of the DTMs. Validation in this respect has only been done for the MSL test site. Below is a list of tests performed with a short description of the purpose of the single tests. This was only fully performed for the CTX datasets. Only the colour-coded overlay was used.:

Visual control:

1. Inspection of shaded relief
   - Qualitative assessment of resolved detail
   - Visualization of noise characteristics
   - Visualisation of height artifacts and surface patterns
2. Colour coded overlay
   - Visualization of gross artifacts and internal model deformation and lateral shifts, but not suited for fine detail
3. Contour lines
   - Evaluation of DTM height representation in comparison with visible surface features in the ortho-rectified image
   -

Numerical measures

N.B. For HiRISE only the first of these methods was applied using the CTX DTM products

4. Height statistics
   - Statistical evaluation of the provided DTMs (minimum, maximum, and standard deviation values of height) in comparison to the reference HRSC DTM
5. Crater statistics for selected data sets
   - Representation of craters visible in the ORI in the DTM providing a statistical value for feature size that is still resolved in the DTM
   - Effective resolution of DTM – comparison of craters visible in the ORI and in the DTM

To validate the provided data sets a common reference map projection was established between the respective reference HRSC dataset by resampling the HRSC data to the same map projection and resolution as the provided data. This kept the data to be validated in the original sampling and quality.

4 Validation results

4.1 MER-A

4.1.1 Shaded reliefs

Due to the resolution of the HRSC data products no comparison with respect to these is performed. Instead the general appearance of the shaded version for the delivered DTM is considered.

The shaded DTM version of the UCL MER-A product (Figure 4-1 A) displays an apparently very smooth terrain but showing a frequent horizontal pattern approximately perpendicular to the long site of the visible scene. Clearly represented surface features show large dimensions compared to the raster size (nominal resolution) of the DTM. The mountains and hilly areas in the centre and South-West of the scene appear rather blurry and with little sharply defined morphological features. Outliers appear to be concentrated on the North-West facing slopes of craters and South-East slopes of hills. This is likely due to the shadow casting in the input images used (see also ORI). Looking at the entire scene there is an impression of the already mentioned undulation that appears to have a systematic background.

In the detailed view of the UCL DTM a smear in SSW to NNE direction appears to be present. This effect does smooth the scene and covers a previously observed, sharply pronounced fabric like pattern in some areas very well but leaves this previous pattern in other regions still recognisable (cf. Figure 4-2 (2)). Due to the smoothing now applied, there is also little noise in the DTM visible. This said, it also appears to represent a shallow relief with few sharp contours.

The UoS DTM, (Figure 4-1B), shows significant noise in the central part of the covered area of the DTM. The southern area and northern parts of the scene appear to represent the surface well with an apparent unsystematic but clearly recognisable noise. Crater rims look flattened and the slopes of the hills, i.e. in the South-West, appear to be cascaded. The flat planes in the northern part of the DTM show a slight undulating pattern that could be related to a systematic effect.

Detailed displays of the UoS DTM are shown in Figure 4-3.

Comparing the products from UCL and UoS, the appearance of the UCL DTM is smoother and more detailed than the UoS DTM. At a first glance, the impression is that more and smaller craters are visible in the UCL DTM. There is less noise in the UCL DTM than in the UoS DTM but more apparent systematic effects are visible in the UCL product.

These undulations are believed to be due to jitter being detected in the UCL processing due to the extreme sensitivity of the Adaptive Least Squares Correlation employed in the image matching. They have also been noted in UoS products of other areas and only appear when the contrast is very low in the input images as is the case here.

Shown in Figure 4-4 is a hill-shaded view of the HiRISE DTM. A subtle striping can be observed running in the top to bottom direction perpendicular to the base of the image and parallel to the sides. This is most likely due to imperfections in the radiometric decalibration. No obvious examples of jitter are shown.

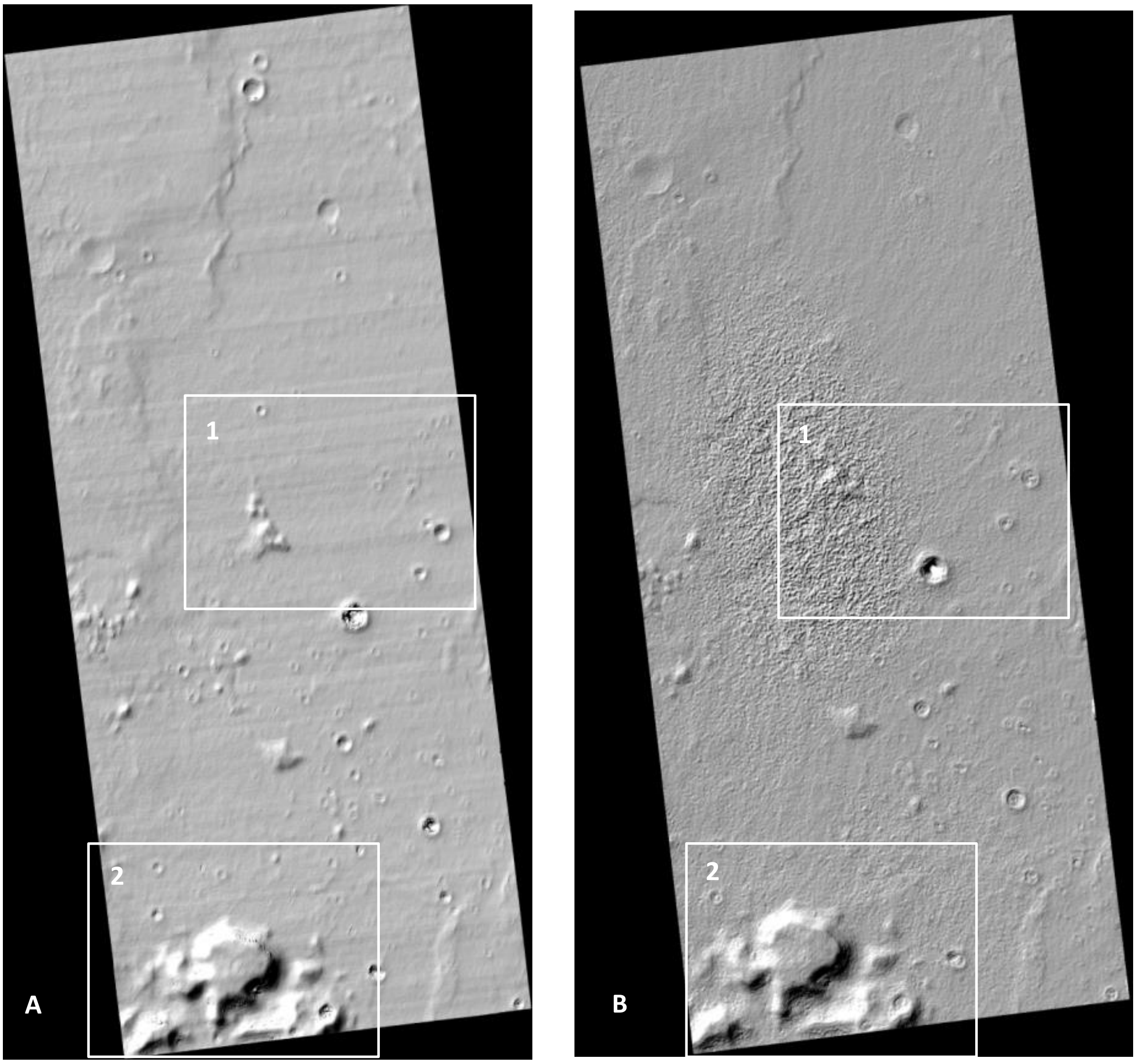


Figure 4-1: Overview shaded CTX DTM MER-A site derived by UCL (A) and UoS (B). See Figure 4-2 for details of marked areas of the UCL CTX DTM and Figure 4-3 for details of the UoS CTX DTM.

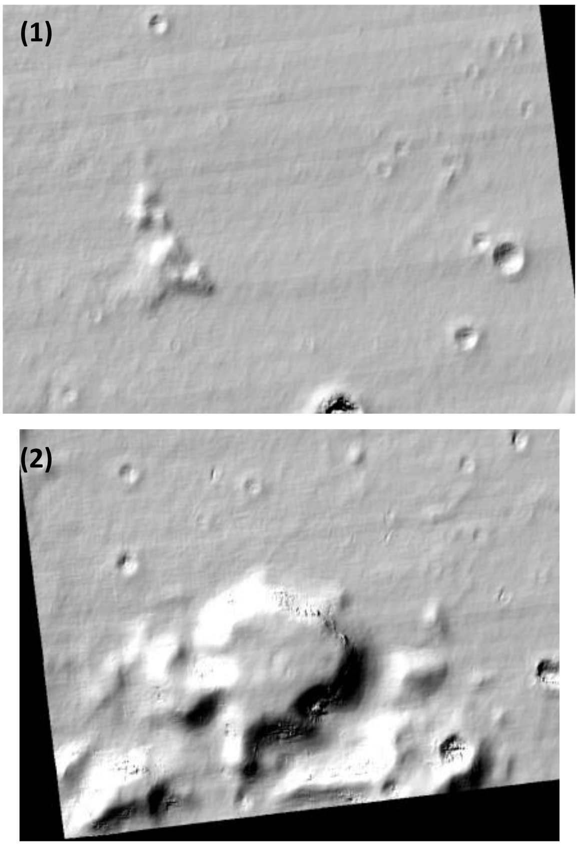


Figure 4-2: Details of UCL CTX DTM.

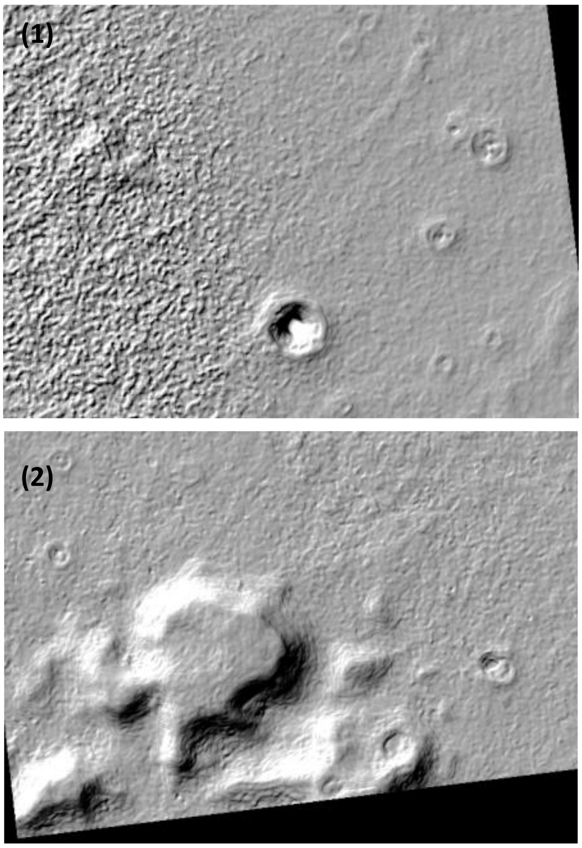


Figure 4-3: Details of UoS CTX DTM.

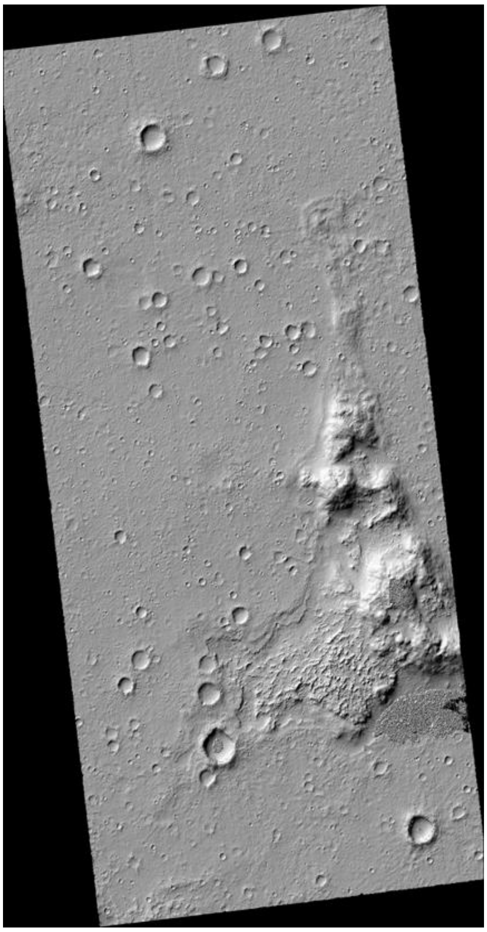


Figure 4-4 Hill-shaded view of UCL HiRISE DTM

4.1.2 Colour Coded Overlay

Here the height values derived from the delivered DTMs are displayed as overlay over the ortho-rectified image. For the UoS relief the CTX ORI delivered by UCL was used. The CTX ORI delivered by UCL was used as a base map for the UCL relief.

Figure 4-5 shows the produced overlays. On the left hand side the colour coded UCL DTM heights are displayed over the UCL CTX ORI that was delivered. Good agreement between the colour coding and the visible topography is present, but this can only be assessed at a scale range >>100m by this technique. At these moderate scales, it can be demonstrated that the colours follow the surface features in the ORI consistently and craters and slopes can be identified from the height information. At the accuracy level of >>100m.

The colour scale also emphasises prominent relief features well such as for example a slight depression south-west of Columbia Hills where a different colours in comparison to the surroundings is noticeable.

The right hand display of Figure 4-5 shows the colour coded heights of the UoS DTM over the CTX ORI delivered by UCL. Colour coding agrees with the visible topography from the ORI only partly, as a radially distributed height offset pattern is also visible. Columbia Hills can be identified as a hill from the colour coding. However, in the surroundings of Columbia Hill colours – indications of rough unstable terrain – do not agree with the visible topography that appears to be mostly flat with a few small but well defined craters. Judging based on the colours of the terrain in the North and in the South is elevated in comparison with the central area. The latter appears to form an elliptical depression – almost like a vignetting effect – that could indicate a systematic effect.

Note that colour ramps, associated to heights, in Figure 4-5 differ only slightly between right and left display.

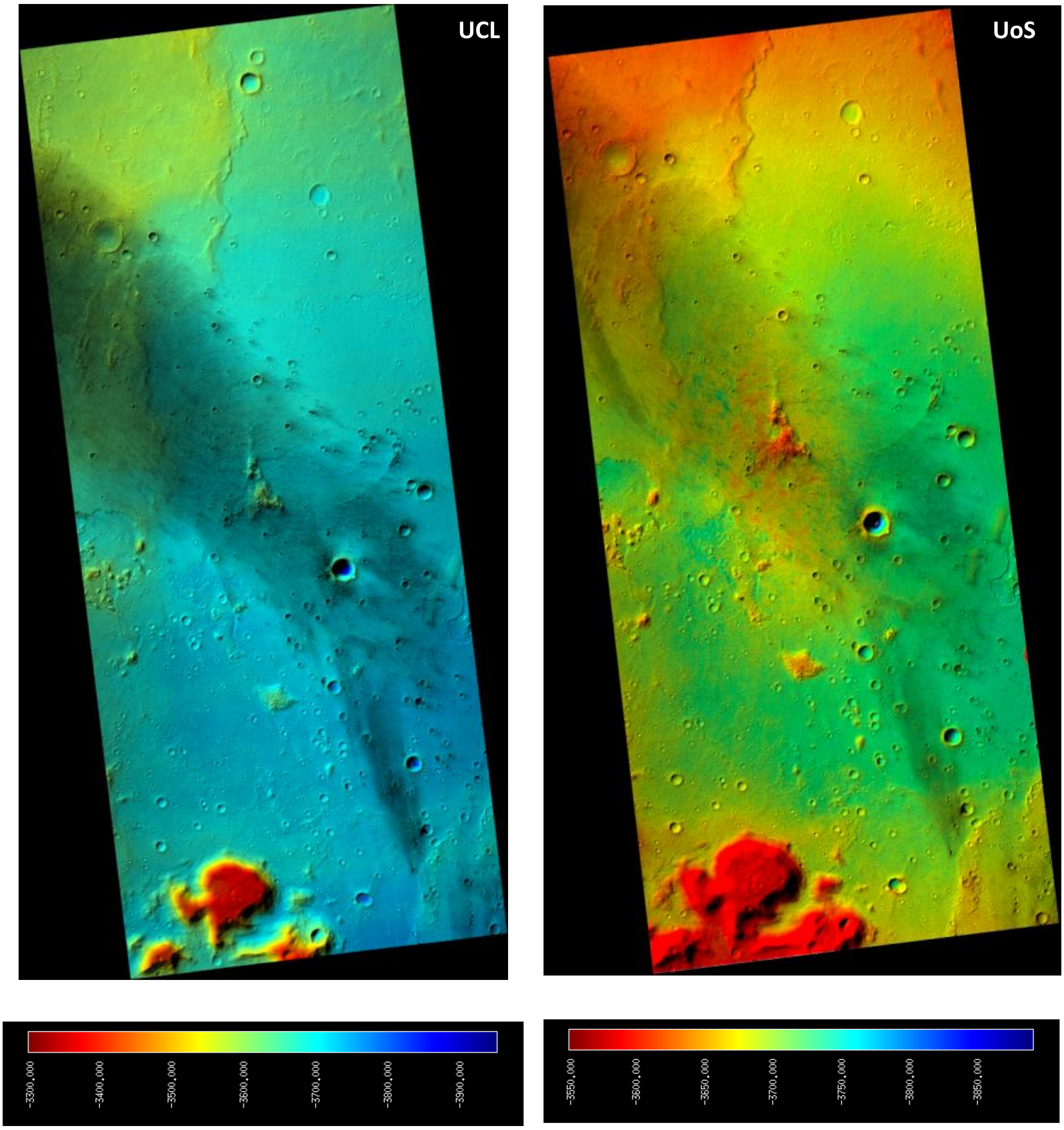


Figure 4-5: Colour coded height in comparison to the CTX ORI. Left UCL DTM heights over the CTX ORI; Right UoS DTM heights over the CTX ORI.

In Figure 4-6 a fluvial-like feature can be clearly observed in the UCL HiRISE DTM extending from the two sets of hills and running to features in the west with a set of 3 craters in a row.

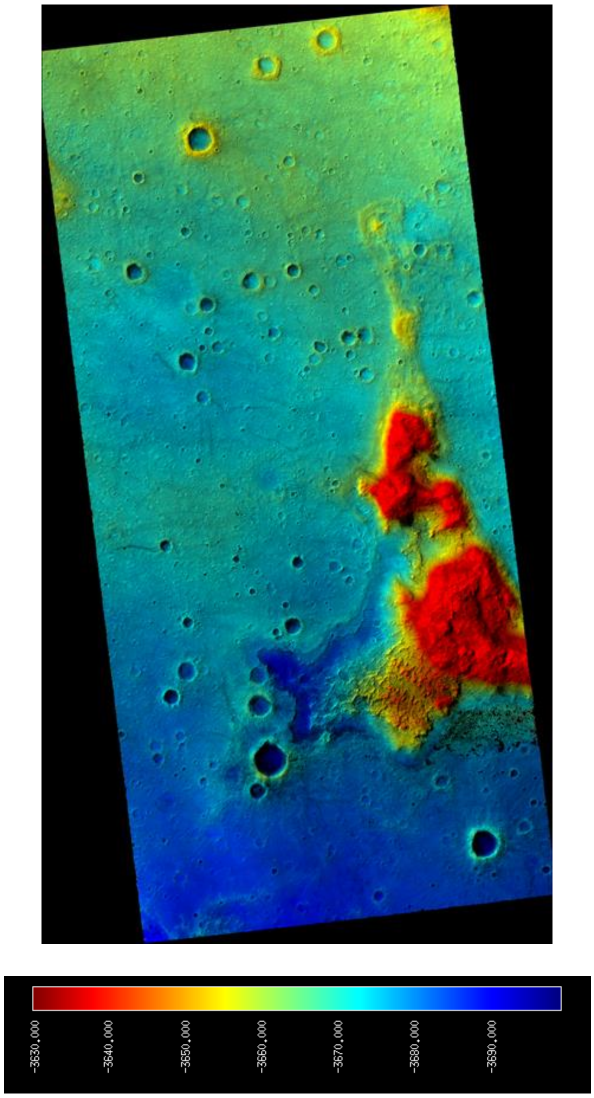


Figure 4-6 Fusion of UCL HiRISE DTM with ORI

4.1.3 Contour lines

Contour lines should represent the general morphology of the terrain. These should follow around hills and should coincide well with the visible features in the ORI. Here the UCL CTX ORI is applied as a base map for all derived contour lines. Hence, a shift in the registration between the ORI and the DTM data set that is used to compute the contour lines could be visible.

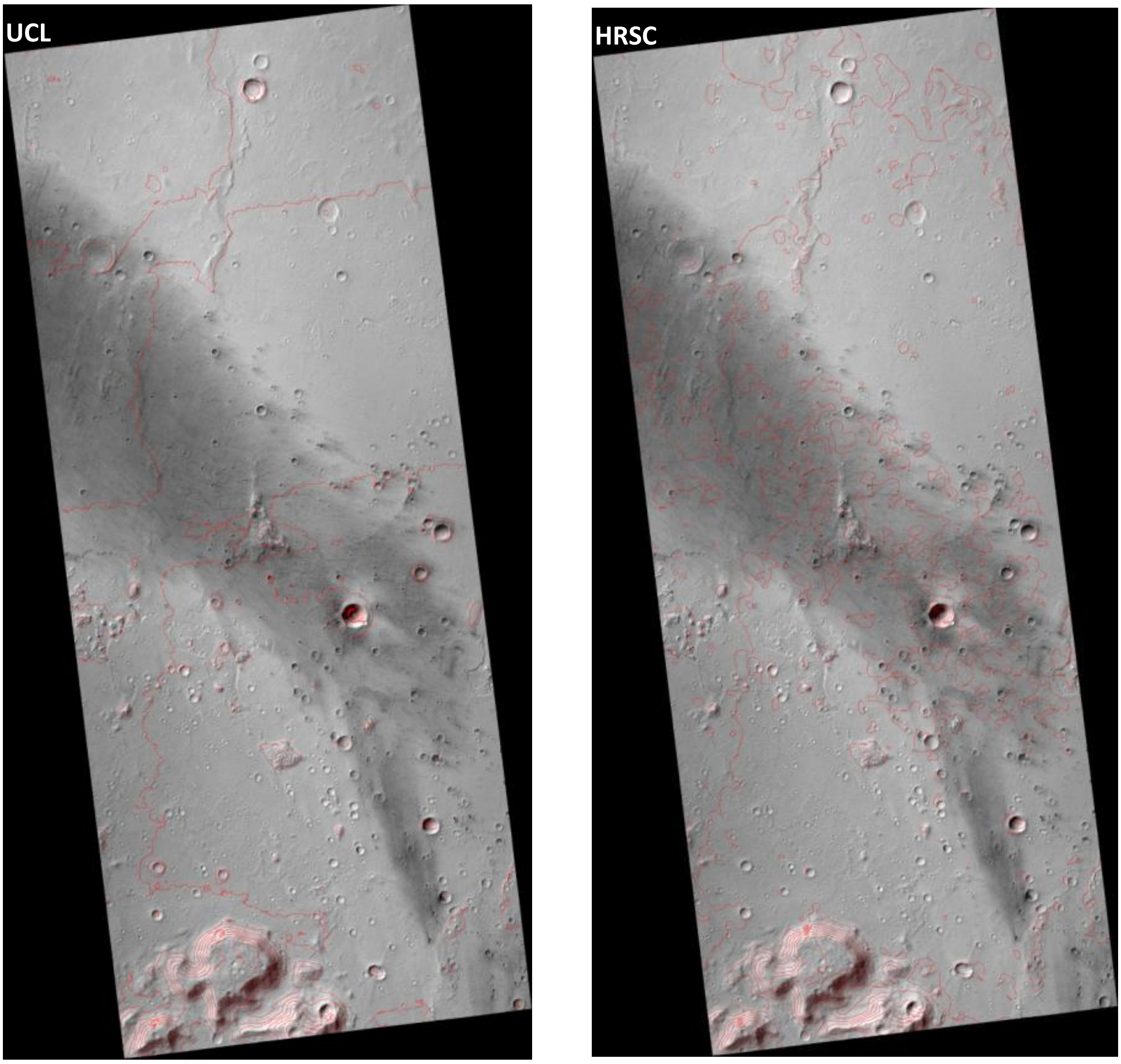


Figure 4-7: Comparison of contour lines and CTX ORI. Left contour lines computed from UCL CTX DTM. Right contour lines computed from HRSC DTM covering this area. Both have 50 m spacing between the contour lines.

The left display in Figure 4-7 shows the contour lines of the UCL DTM over the provided CTX ORI. These are well defined and approximately follow visible craters and peaks or hills. The flat terrains are rather undefined and the contour lines become less defined and do not seem to follow the shallow slope of the terrain. On sloped terrain, the contour lines follow the relief more consistently, although considerable smoothing is observed on distinct morphological elements.

The right display of Figure 4-7 shows in comparison the HRSC contour lines on the CTX ORI delivered by UCL. Contour lines are somewhat smoother around the larger visible surface features in comparison to the UCL DTM – i.e. the large crater South-East of Columbia Hills. Prominent features like hills, craters and slopes are well represented by the contour lines. However, offsets in slightly different direction with respect to the shown morphology in the CTX ORI are present.

This suggests that there is a distortion across the scene between the HRSC data co-registered with MOLA and CTX data.

Comparing the contour lines between UCL and HRSC, both follow the visible contours of the hills in the south-west of the scene approximately and in a very similar way. The larger craters of the scene and the Columbia Hills are represented in both data sets, UCL and HRSC DTM, but differ in

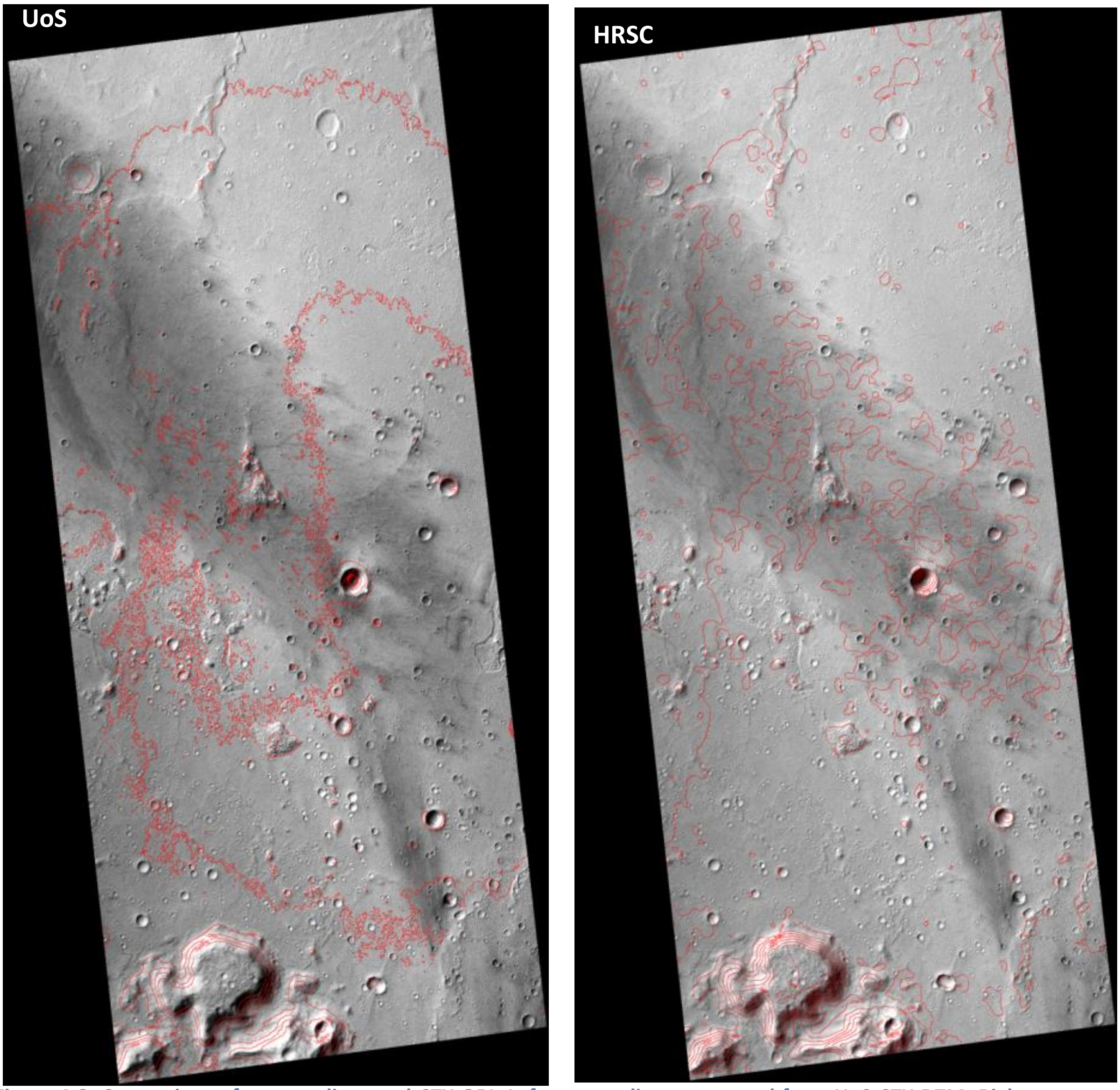


Figure 4-8: Comparison of contour lines and CTX ORI. Left contour lines computed from UoS CTX DTM. Right contour lines computed from HRSC DTM covering this area. Both have 50 m spacing between the contour lines.

detail. No clearly apparent improvement of the CTX DTM over the HRSC DTM can be demonstrated for this area and by this technique, in spite of the much higher (factor 3) nominal resolution of the CTX DTM

The left display in Figure 4-8 shows the contour lines of the UoS DTM. These are well defined in craters and peaks or hills. In smooth and flat areas the lines become ill defined and do not seem to follow the terrain in a likely path. This reflects the noise in the DTM already visible in Figure 4-1. Contour lines in the northern part of the scene are not following the visible terrain – and are not comparable to HRSC – but further the impression that the DTM is affected by a systematic artefact that produces a global dip towards the centre of the scene (cf. Figure 4-5 right).

In comparison with the HRSC contour lines, Figure 4-8 (right), the UoS is less detailed and i.e. the hills in the South-West show a numerical effect related to discrete height values where a smooth appearance should be expected from the image, with stepped slopes compared to the HRSC.

4.1.4 Statistical measures

Table 4-1 and Table 4-2 show height statistics figures for the CTX MER-A DTM from UCL and UoS. As described above, the HRSC DTM was resampled to fit to the data to be validated. Due to the different resolutions delivered between UCL and UoS, there is a discrepancy in the number of pixel elements evaluated.

The UCL DTM (Table 4-1) has a height minimum that is 60 m lower in comparison to the HRSC DTM. In contrast the Maximum is 32 m higher in elevation than the maximum value of the HRSC DTM. As a consequence, the range of heights of the UCL DTM is 90 m larger compared to the HRSC DTM. This could be attributed to the better resolution the UCL DTM is provided in and thus the higher detail to be expected. However, the average height value is comparable with the HRSC DTM value and differs by only 6 metres.

The observed standard deviation for the UCL CTX DTM is higher compared to the HRSC DTM. This could be due to the pattern observed that introduces additional noise to the scene. Another source for the higher standard deviation could be the increased detail of the CTX DTM in comparison to HRSC. Though, this appears to be unlikely since the observed effective resolution of the DTM is in the order of 75 m/pixel, as was reported in the previous section.

Table 4-1: Statistical data of UCL MER-A DTM

	HRSC DTM	UCL DTM	HRSC – UCL DTM
Number of Elements:	4,593,037	4,593,037	4,593,016
Minimum [m]:	-3891.83	-3951.59	-121.331
Maximum [m]:	-3362.11	-3330.80	125.094
Height range [m]:	529.72	620.79	246.425
Average DN Value [m]:	-3678.36	-3672.06	-6.29933
Standard Deviation [m]:	46.6395	54.9509	17.7338

The UoS DTM (Table 4-2), on the other hand, shows a comparable standard deviation with respect to the HRSC DTM. The minimum / maximum heights that are in a similar range to the height range of the HRSC DTM. Only the minimum height value is approximately 60 m below the minimum of the HRSC DTM. The source is seen in the bowl shape of the DTM and the noise in the central parts that have been observed in the colour overlay and the shaded relief.

Table 4-2: Statistical data of UoS MER-A DTM

	HRSC DTM	UoS DTM	HRSC – UoS DTM
Number of Elements:	2,261,653	2,261,653	2,261,642
Minimum:	-3891.82	-3951.42	-321.006
Maximum:	-3362.09	-3361.91	106.930
Height range [m]:	529.73	589.51	427.936
Average DN Value:	-3684.68	-3678.82	-5.85485
Standard Deviation:	45.6996	46.2945	24.9589

The equivalent figures for the HiRISE and its comparison with the validated CTX DTM are shown in Table 4-3. This indicates that there may be a height offset here which is not fully accounted for by the co-registration process. The standard deviation is very small.

	CTX DTM	HiRISE DTM	CTX – HiRISE DTM
Number of Elements:	88,182,234	88,182,234	88,182,234
Height range [m]:	101.63	120.84	126.348
Average Height [m]:	-3688.85	-3669.31	-19.539
Standard Deviation [m]:	14.078	14.056	5.851

Table 4-3 Statistics of the UCL CTX, HiRISE and CTX-HiRISE height differences

4.2 MER B

4.2.1 Shaded reliefs

Due to the resolution of the HRSC data products (150m) no comparison with respect to these is performed. Instead the general appearance of the shaded version for the delivered DTM is considered.

The shaded DTM version of the MER-B UCL product Figure 4-9 (A) displays the area showing significant noise. The large crater, Endeavour Crater, in the East is well observed but shows reconstruction artefacts. Medium sized craters appear in the scene but seem to be represented as being too shallow. Victoria Crater in the north-west of Endeavour Crater is well observed. A fabric like pattern is noticeable in the northern flat terrain and South-West of Endeavour Crater. The systematic “jitter” artefact is equally present as in the data product for MER-A.

Details of the UCL DTM reveal a pattern that appears to be like a fabric which is described in Tao et al. (2016) This is more pronounced in some parts than in others and well observed in Figure 4-10 (1) & (2). This pattern adds some noise to the DTM and masks details in the scene.

The UoS DTM Figure 4-9 (B) shows significant noise across the covered area. A global systematic linear high frequency pattern is visible across the scene. Endeavour Crater in the east of the scene is recognizable but not very well defined. Likewise, Victoria Crater is hard to be recognized in the hill shaded UoS DTM. Flat areas in the northern part of the scene are affected by strong noise and only a few medium sized craters are reconstructed.

Detailed displays of the UoS DTM are shown on the right side of Figure 4-10. Here the strong noise in the northern flat terrain is shown (1) that does not provide any sensible information for a scientific investigation. In Figure 4-10 (2) the high frequency pattern is clearly visible. It appears to follow the terrain rather than being in parallel with e.g. the lines of the input images and can thus be attributed to an artifact introduced by the processing chain.

Comparing the products from UCL and UoS the UCL DTM does show the area much better defined than the UoS DTM. Craters are sharper in the UCL DTM and crater rims appear to be better defined. Though the UCL DTM is not considered to be a high quality product, based on this qualitative assessment of the data and due to the described artefacts, it represents the surface better than the UoS DTM.

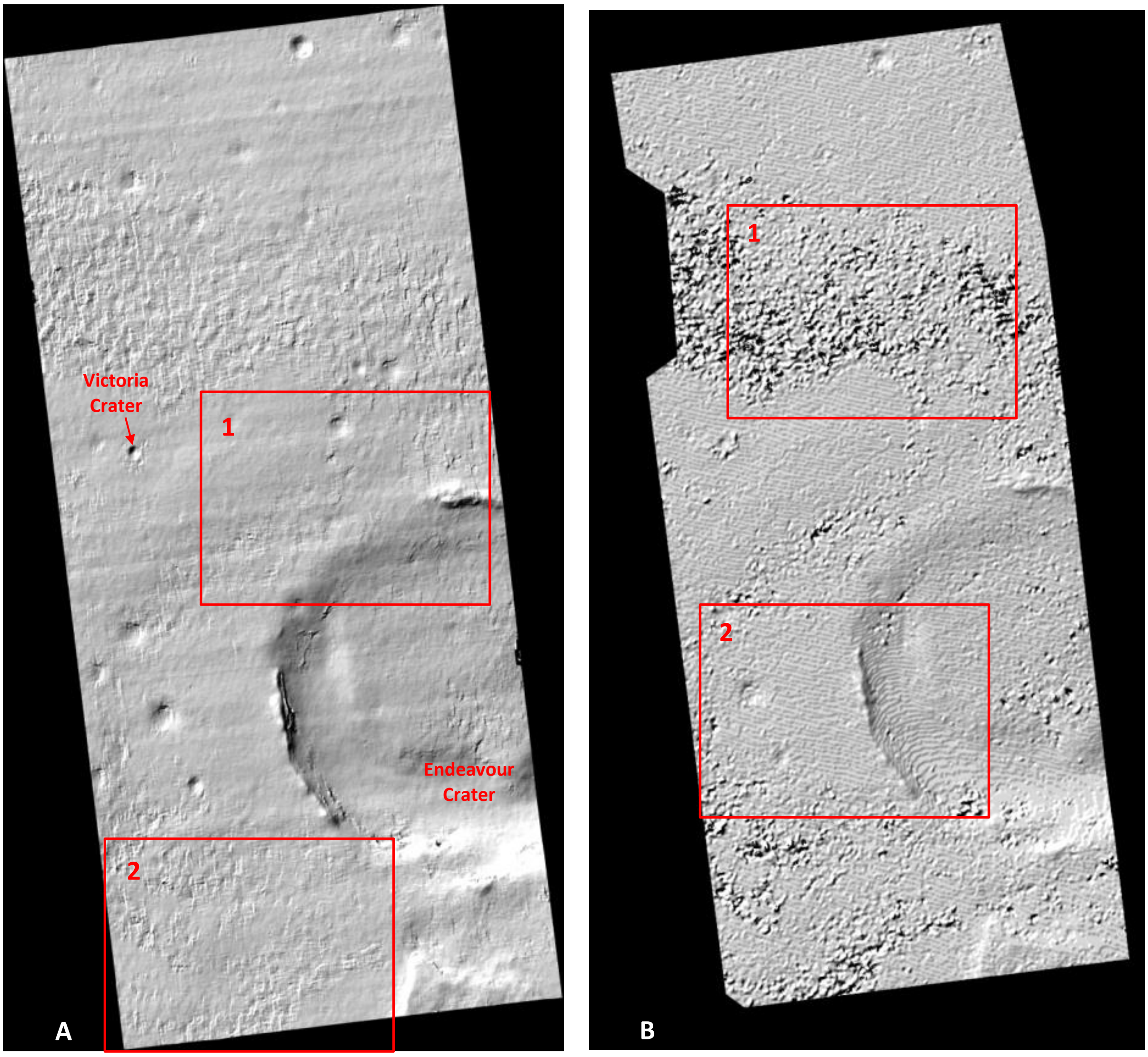


Figure 4-9: Overview shaded DTM MER-B site derived by UCL (A) and UoS (B). See Figure 4-10 for details of marked areas of the UCL DTM and Figure 4-10 for details of the UoS DTM.

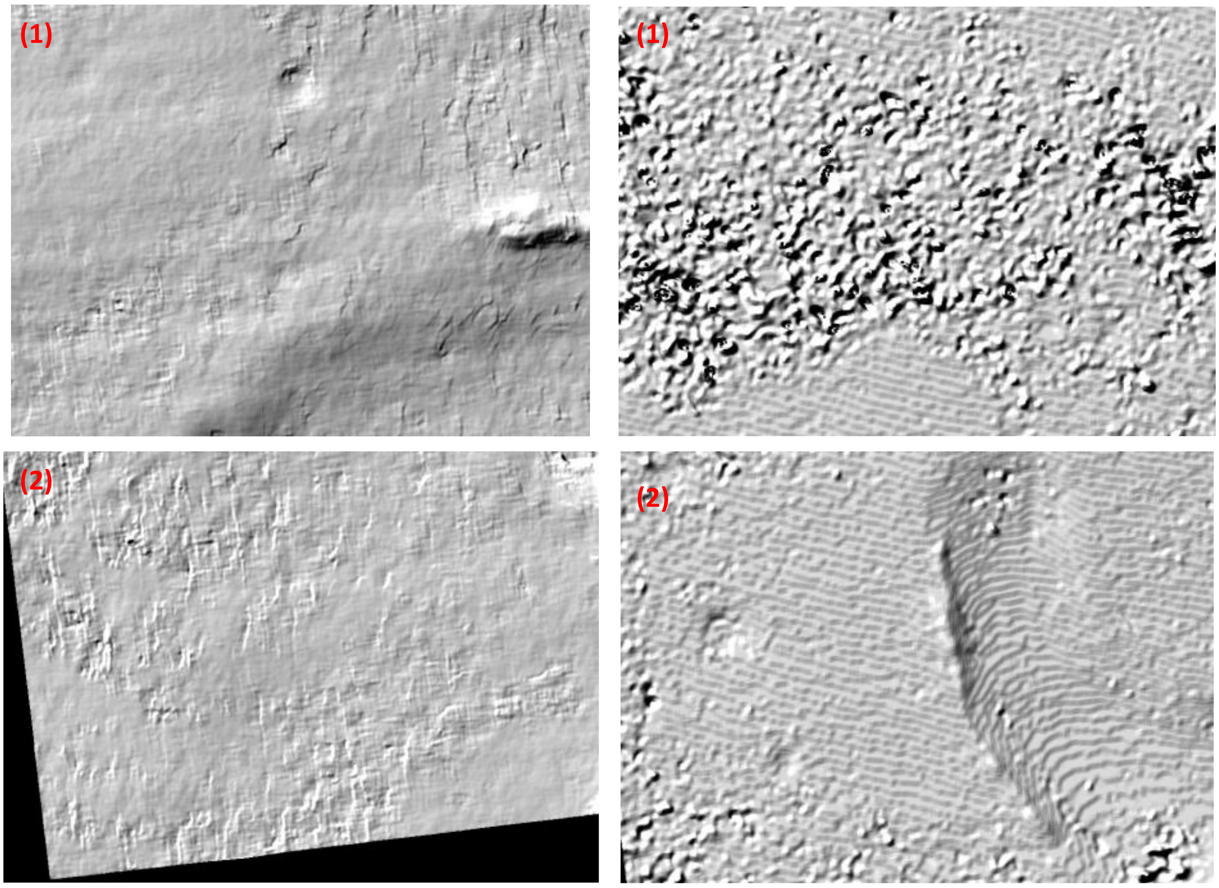


Figure 4-10: Details of the MER-B DTM products from UCL (left) and UoS (right).

The HiRISe DTM shown in Figure 4-11 shows the striping due to radiometric decalibration issues as well as details of the Victoria crater. Little relief is visible aside from the sides of Victoria crater.

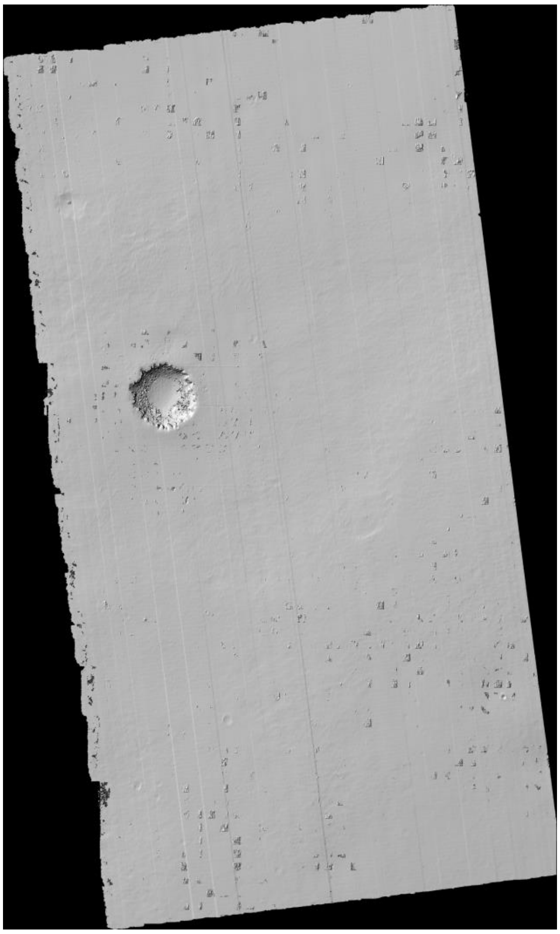


Figure 4-11. Hill-shaded HiRISE DTM of the MER-B Victoria crater region

4.2.2 Colour Coded Overlay

Here the height values, derived from the delivered DTMs, are displayed as colour overlay over the ortho-rectified image. For the UoS relief the CTX ORI delivered by UoS was used. The CTX ORI delivered by UCL was used as a base map for the UCL relief.

Figure 4-12 shows the produced overlays. On the left hand side the colour coded UCL DTM heights are displayed over the UCL CTX ORI that was delivered. Here, a good agreement between the colour coded heights and the visible surface in the UCL CTX ORI is present. The areas that have been identified as areas containing increased noise are likewise visible and can be clearly linked with regions of little to no texture in the CTX image.

The coloured height information displays depressions in the visible craters, however, some well-defined craters with sharp rims, as judged from the ORI, appear to be little distinguishable from the height information. Little change of colour is visible inside the mid-sized craters – including Victoria crater – which would be expected.

The right hand display of Figure 4-12 shows the colour coded heights of the UoS DTM over the CTX ORI delivered by UCL. The already seen linear pattern due to jitter across the scene is also well observed in the colour coded heights. Similar, the areas with increased noise can be made out by the irregular and random colouring in the northern parts of the scene and in the south-west of the Endeavour crater. Craters appear to be better represented in comparison to the UCL colour coded overlay. This might, however, be a matter of representation – the colour bar for the UoS display stretches over a smaller height range than the colour bar for the UCL DTM.

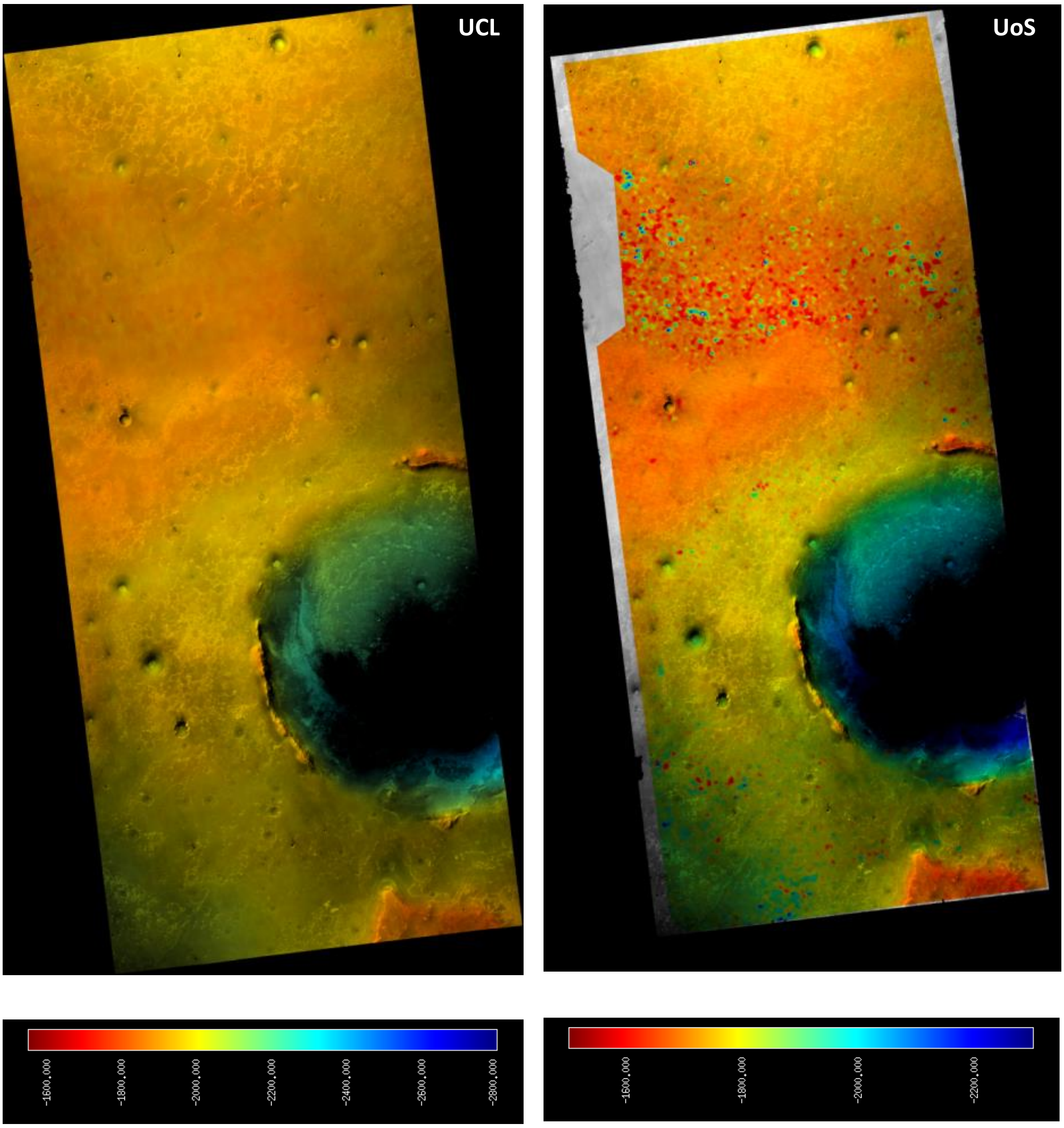


Figure 4-12: Colour coded height in comparison to the CTX ORI. Left UCL DTM heights over the CTX ORI; Right UoS DTM heights over the CTX ORI.

In Figure 4-13 we can observe the HiRISe DTM with features showing the remnants of previous fluvial action just visible. The features in Victoria crater are well observed.

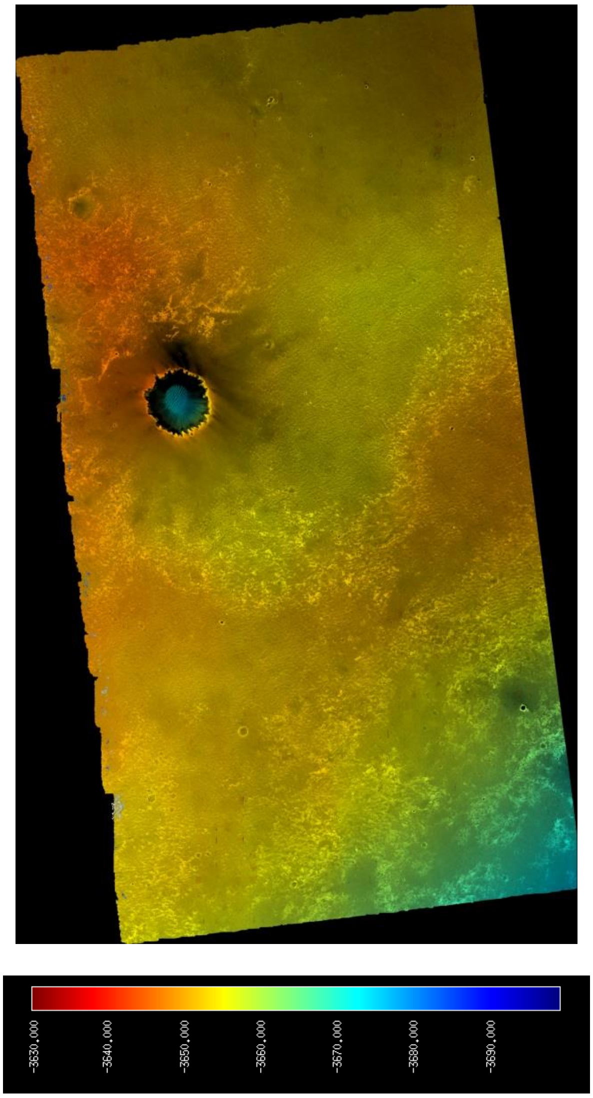


Figure 4-13. Colourised HiRISE DTM using colour-coded height

4.2.3 Contour lines

Contour lines should represent the general morphology of the terrain. These should follow around hills and should well coincide with the visible features in the ORI. Here the UCL CTX ORI was applied as a base map. Contour lines were computed based on the delivered CTX DTMs and the reference HRSC DTM.

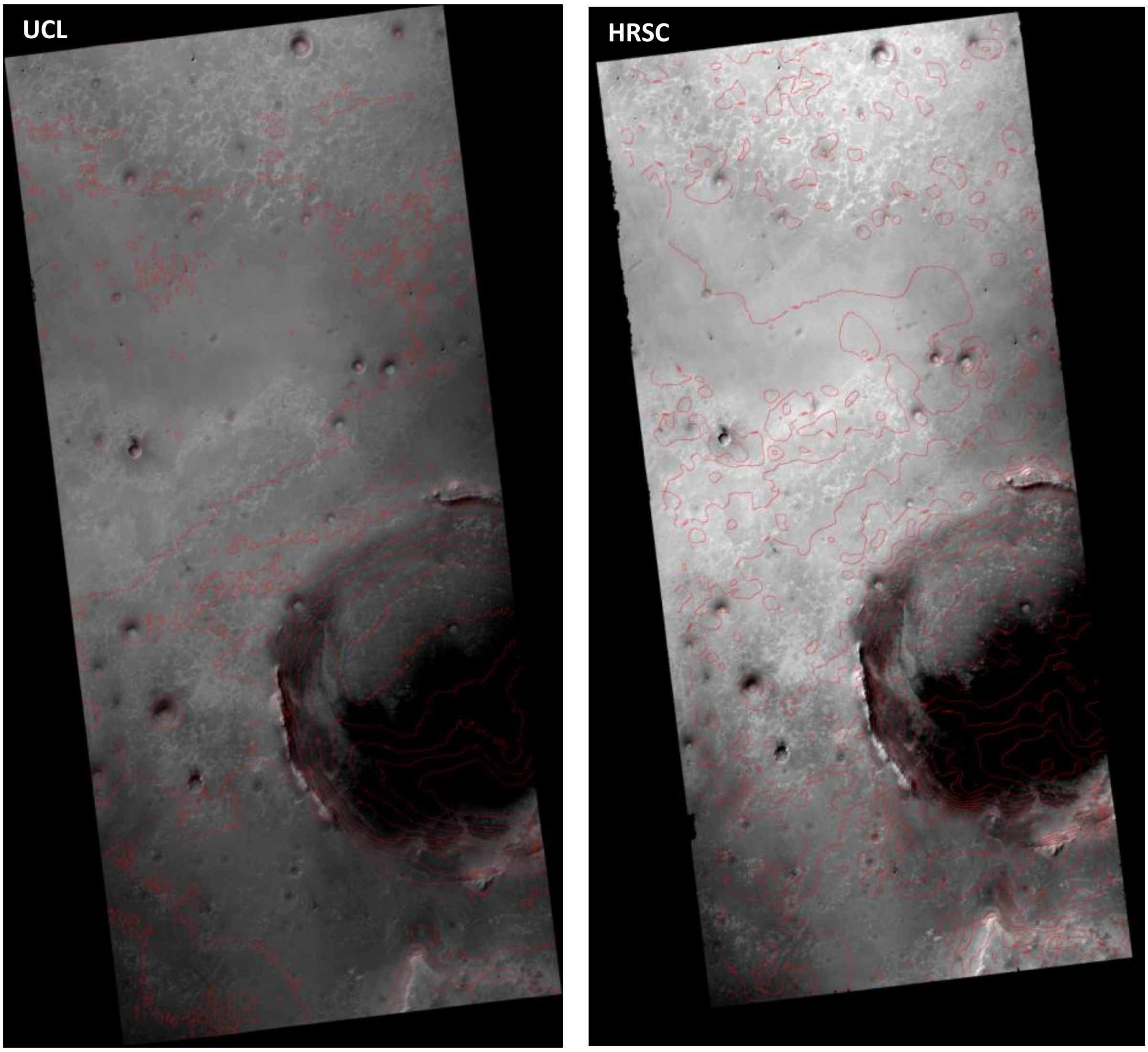


Figure 4-14: Comparison of contour lines and CTX ORI. Left contour lines computed from UCL CTX DTM. Right contour lines computed from HRSC DTM covering this area. Both have 50 m spacing between the contour lines.

The left display in Figure 4-14 shows the contour lines of the UCL DTM. Contour lines are well defined in the Endeavour and Victoria craters and where the terrain changes significantly. In flat areas the contour lines appear scattered, irregular and disconnected. A few craters, other than the two mentioned, are represented by the contour lines.

The right display shows, in comparison, the HRSC contour lines on the CTX ORI delivered by UCL. In comparison to the UCL DTM, contour lines are smoother and are not segmented. However, the Endeavour Crater and the Victoria Crater appear to be poorly represented in the HRSC DTM.

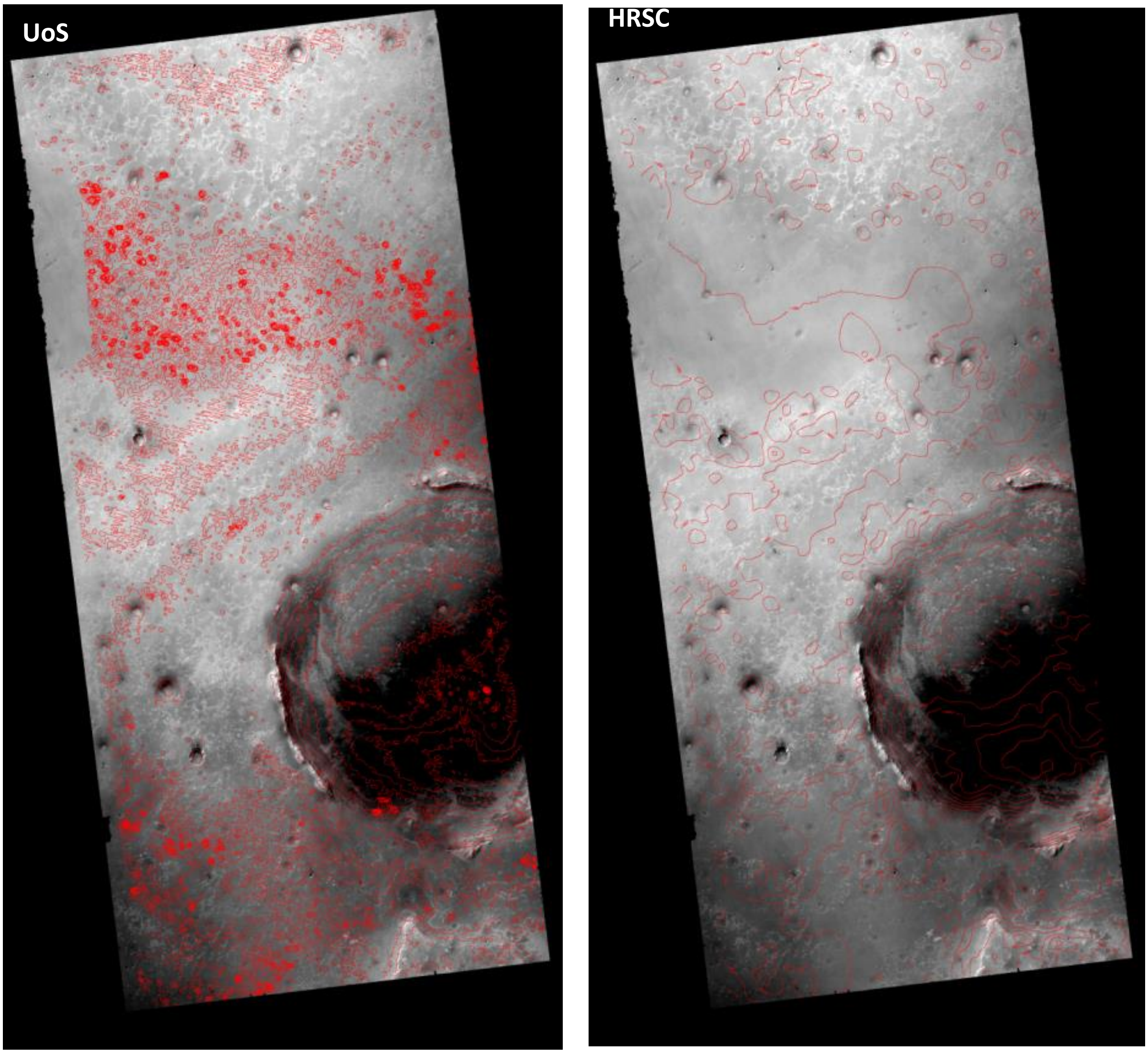


Figure 4-15: Comparison of contour lines and CTX ORI. Left contour lines computed from UoS CTX DTM. Right contour lines computed from HRSC DTM covering this area. Both have 50 m spacing between the contour lines.

The left display in Figure 4-15 shows the contour lines of the UoS DTM over the UCL CTX ORI. Across the entire scene a linear artefact is visibly represented by the contour lines. The lines in the Endeavour Crater and in the northern part are irregularly formed and show small peaks that are randomly scattered across these areas. The regions that had already been identified as very noisy areas can again be well identified in the representation of the contour lines by the many random and very local peaks indicated by the contour lines but not visible in the ORI.

The right display of Figure 4-15 shows in comparison the HRSC contour lines on the CTX ORI delivered by UCL.

4.2.4 Statistical measures

Table 4-3 and Table 4-4 show results of the statistical data analysis for the CTX MER-B DTM from UCL and UoS, respectively. As described above, the HRSC DTM was resampled to fit to the data to be validated. Due to the different resolutions delivered between UCL and UoS, there is a discrepancy in the number of pixel elements evaluated.

The UCL DTM (Table 4-3) has a slightly lower minimum in comparison to the HRSC DTM while the height maximum differs by 400 metres with respect to the HRSC value. However, since the average height value is comparable with the HRSC DTM value and differs by only 26 metres, it is assumed that this maximum height value can be attributed to outliers in either of the two data sets.

The observed standard deviation for the UCL CTX DTM is in the same order as for the HRSC DTM. It would be expected that the standard deviation also correlates with the data set resolution, however, the observed noise in parts of the scene will significantly contribute to this number.

Table 4-3: Statistical data of UCL MER-B DTM

	HRSC DTM	UCL DTM	HRSC – UCL DTM
Number of Elements:	4 629 429	4 629 429	4 629 425
Minimum [m]:	-2445.93	-2458.73	-540.707
Maximum [m]:	-1690.43	-1285.77	143.094
Height range [m]:	755.50	1172.96	683.801
Average DN Value [m]:	-1946.81	-1972.58	25.7694
Standard Deviation [m]:	129.835	122.475	22.8423

The UoS DTM (Table 4-4) on the other hand shows a much larger difference in minimum/ maximum height values and consequently has a much larger range of heights in comparison to the HRSC DTM. The source is seen in the bowl shape of the DTM and the noise in the central parts that have been observed in the colour overlay and the shaded relief. The average of the height values of both DTMs differs by about 150 metres indicating that the UoS DTM is on average 150 meters lower than the HRSC DTM.

Table 4-4: Statistical data of UoS MER-B DTM

	HRSC DTM	UoS DTM	HRSC – UoS DTM
Number of Elements:	2493197	2493197	2493197
Minimum:	-2445.87	-2702.33	-951.115
Maximum:	-1690.14	-911.927	651.683
Height range [m]:	755.73	1790.40	1602.798
Average DN Value:	-1949.88	-1801.35	-148.529
Standard Deviation:	130.911	132.611	35.2642

Table 4-5: Statistical intercomparison of UCL CTX and HiRISE DTMs

	CTX DTM	HiRISE DTM	CTX – HiRISE DTM
Number of Elements:	53,853,617	53,853,617	53,853,137
Height range [m]:	81.07	338.44	352.922
Average Height [m]:	-1883.53	-1883.57	0.0468
Standard Deviation [m]:	10.317	11.401	7.745

The HiRISE DTM is compared with the corresponding CTX DTM and is shown in Table 4-5. The average height difference is tiny and the standard deviation is also very small.

4.3 MSL

4.3.1 Shaded reliefs

Due to the resolution of the HRSC data products, no comparison with respect to these is performed. Instead the general appearance of the shaded version for the delivered DTM is considered.

The shaded DTMs of the MSL UCL data and MSL UoS data are displayed in Figure 4-16. The UCL DTM (A) appears well-defined and detailed. In the planes of the displayed area systematic wave jitter structures are visible. These are considered not to be caused by spacecraft jitter effects as the frequency is too low and wavelengths are too long (cf. Mattson et al., 2009). Along south oriented slopes artificial artefacts are visible. The scene appears smooth and details have in general a rounded appearance. It seems that a filter was applied to smooth noise off the scene that was likewise affecting DTM features.

The close up of the UCL DTM (Figure 4-17) shows a smoothed fabric like pattern in both scenes - Figure 4-17 (1) and (2). The wave structure is also very well visible in the cut out displays for the UCL DTM.

The UoS result in Figure 4-18 (B) shows a clear step pattern across the entire scene. This looks like a discretisation problem as the steps appear to follow the height contours. Besides, the DTM looks very detailed with clear structures and little artefacts. Craters are well defined with sharp crater rims with little outliers across the scene. Due to the overall step pattern the DTM appears rather noisy at global scale.

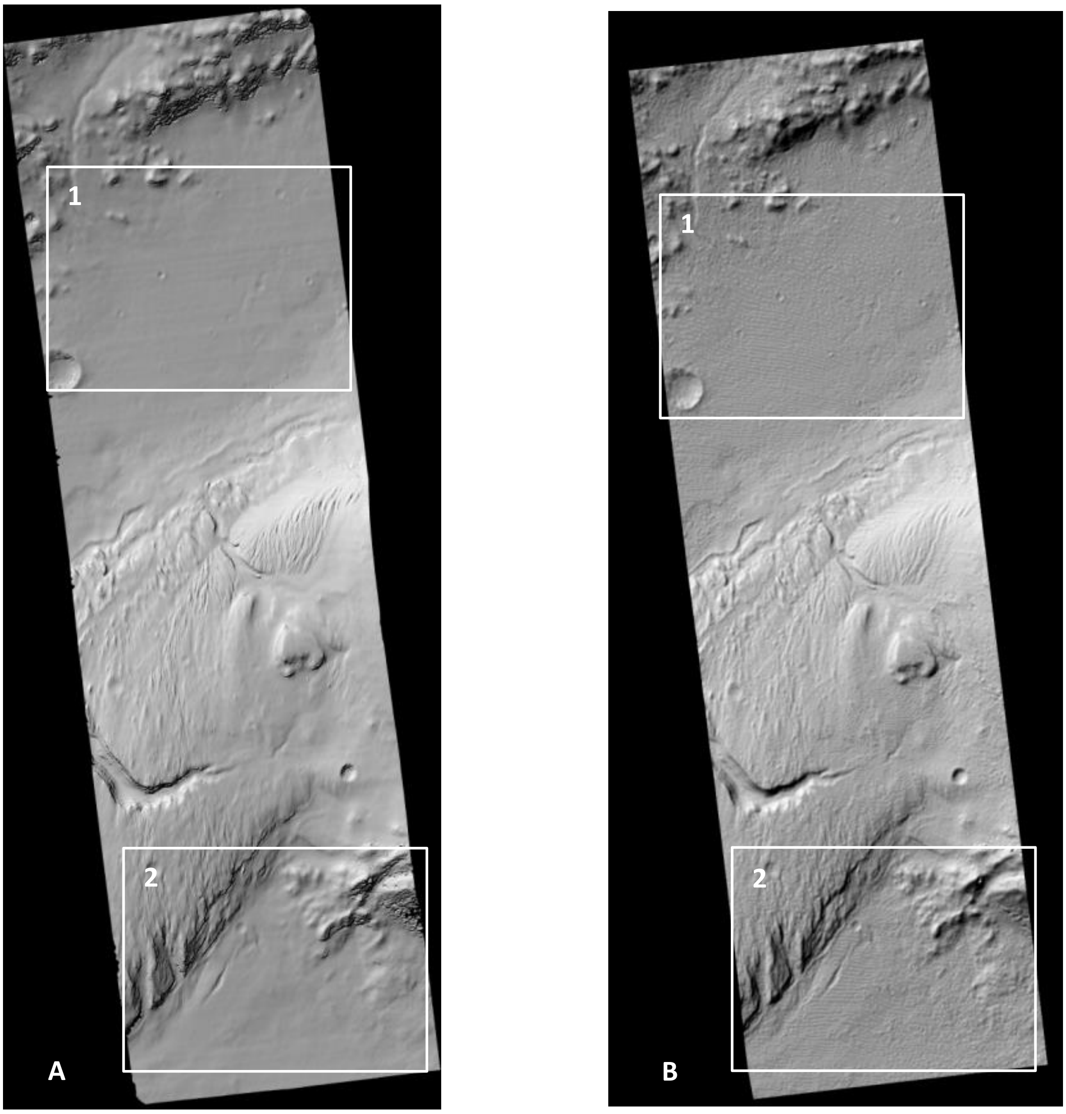


Figure 4-16: Overview of hill-shaded DTM MSL site derived by UCL (A) and UoS (B). See next figure for details of marked areas of the UCL DTM and for details of the UoS DTM.

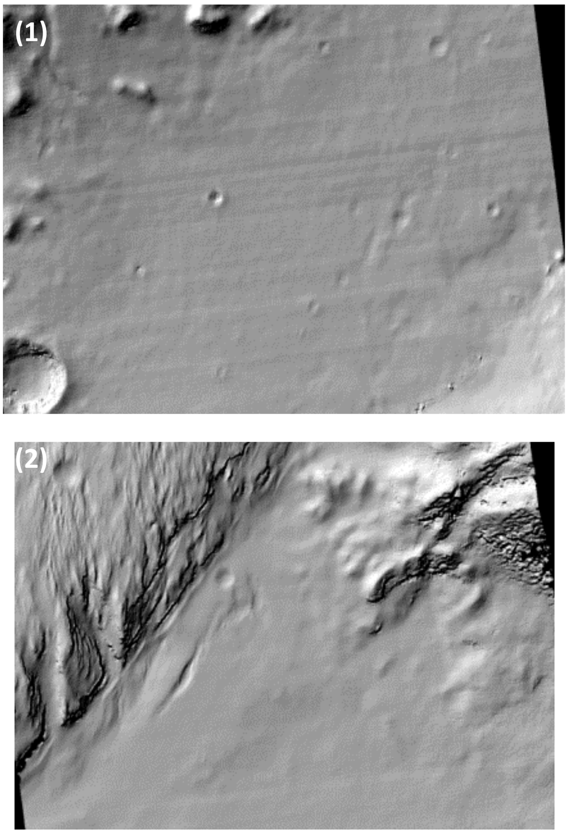


Figure 4-17: Details of UCL CTX DTM.

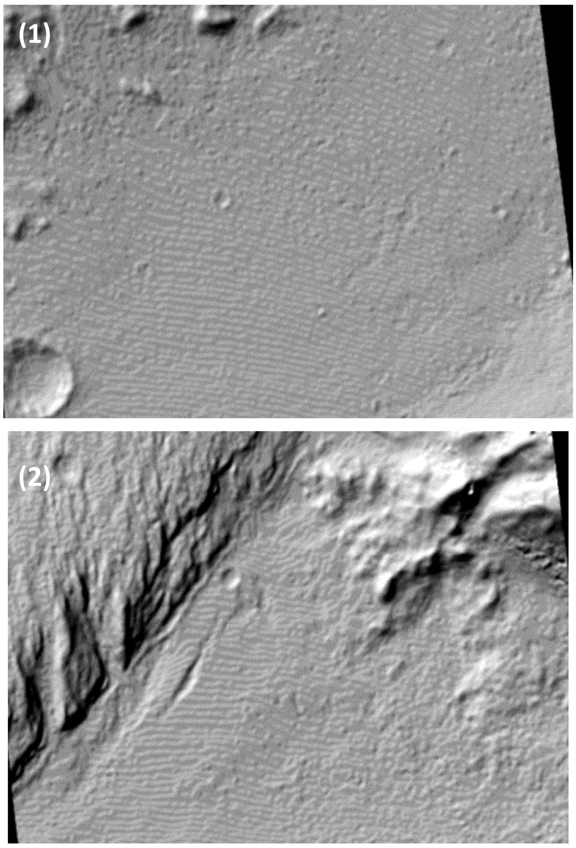


Figure 4-18: Details of UoS CTX DTM.

The UCL HiRISe DTM is shown in Figure 4-19 which exemplifies the fine-scale detail in the DTMs. No striping is observed in either axes parallel to the sides.

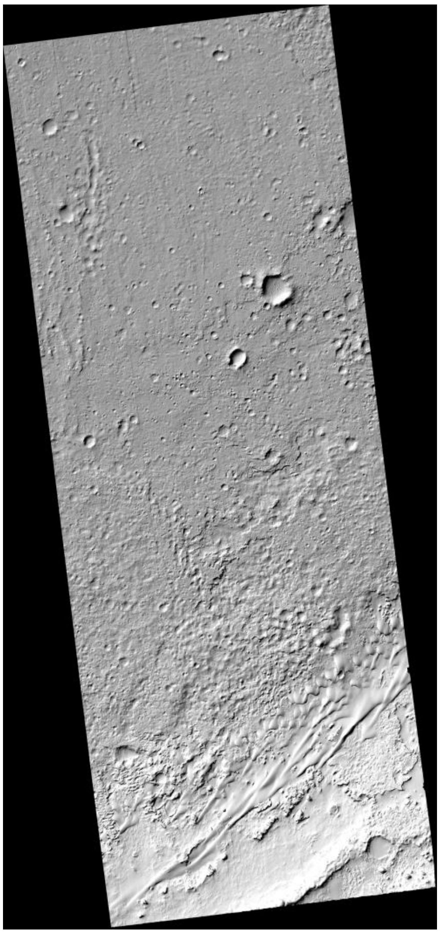


Figure 4-19. UCL HiRISE DTM (hill-shaded) showing fine-scale details of the side of Mt Sharp where the MSL rover is currently climbing.

4.3.2 Colour Coded Overlay

Here the height values derived from the delivered DTMs are displayed as overlays over the ortho-rectified image. For the UoS relief the CTX ORI delivered by UoS was used. The CTX ORI delivered by UCL was used as a base map for the UCL relief.

Figure 4-20 shows the resulting overlays. On the left hand side the colour coded UCL DTM heights are displayed over the UCL CTX ORI that was delivered. Good agreement between the colour codes and the visible topography is presented. For example the gradient of the colours follows the larger surface features in the ORI well. Large slopes and valleys that can be identified in the ORI and from the height information are at the correct location. The colour coding is, however, not sensitive enough to arrive at assessments that are close to the grid resolution of the DTM.

The right hand display of Figure 4-20 shows the colour coded heights of the UoS DTM over the CTX ORI delivered by UCL. The UoS height information also correlates very well with the observable surface of the ORI. There is little difference when comparing the colour coded height information of the UCL and the UoS data. In some areas of the scene – e.g. in the northern parts – the colours appear to differ slightly between UCL and UoS but this is minimal and a clear difference cannot be made out.

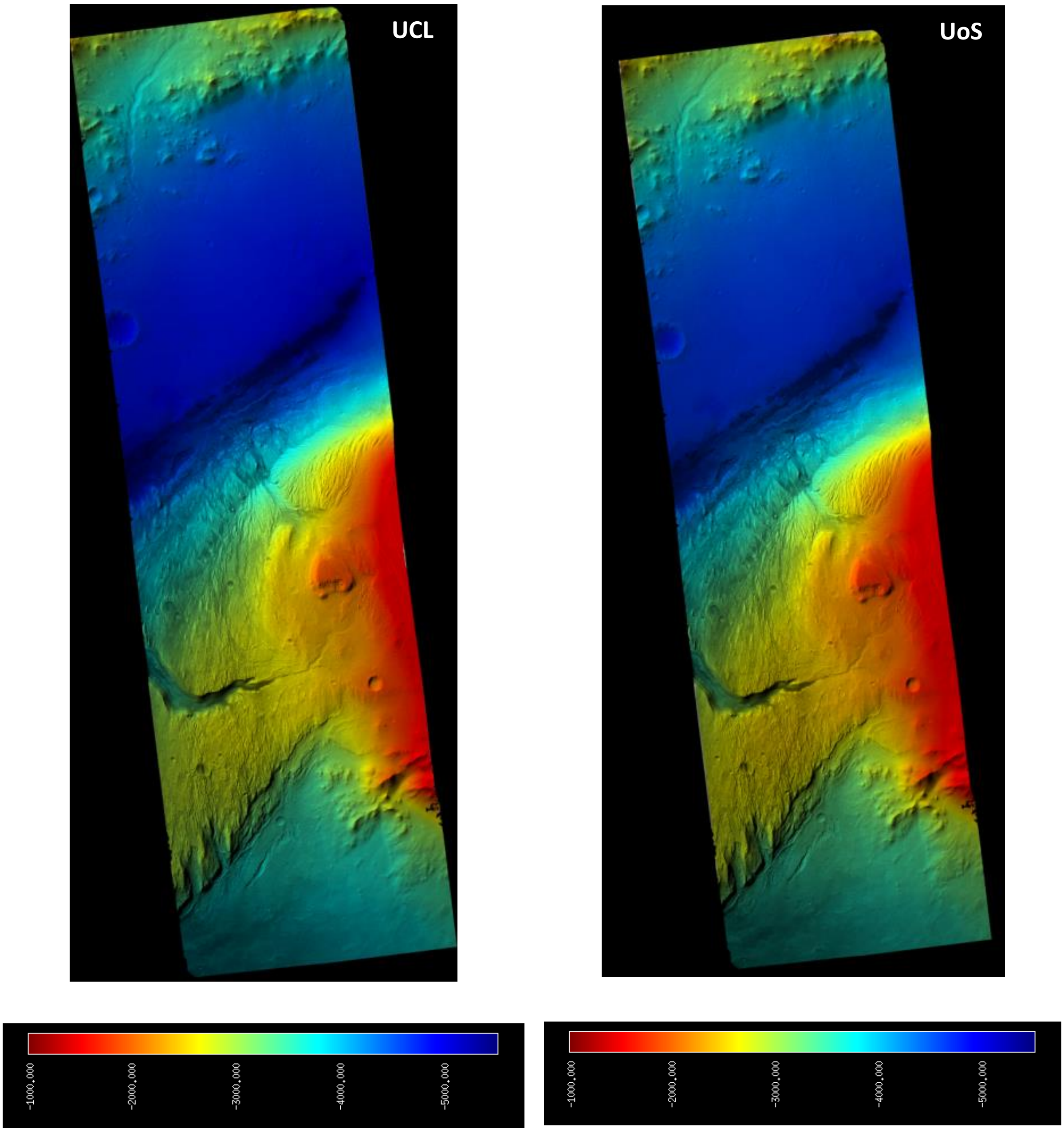


Figure 4-20: Colour coded height in comparison to the CTX ORI. Left UCL DTM heights over the CTX ORI; Right UoS DTM heights over the CTX ORI.

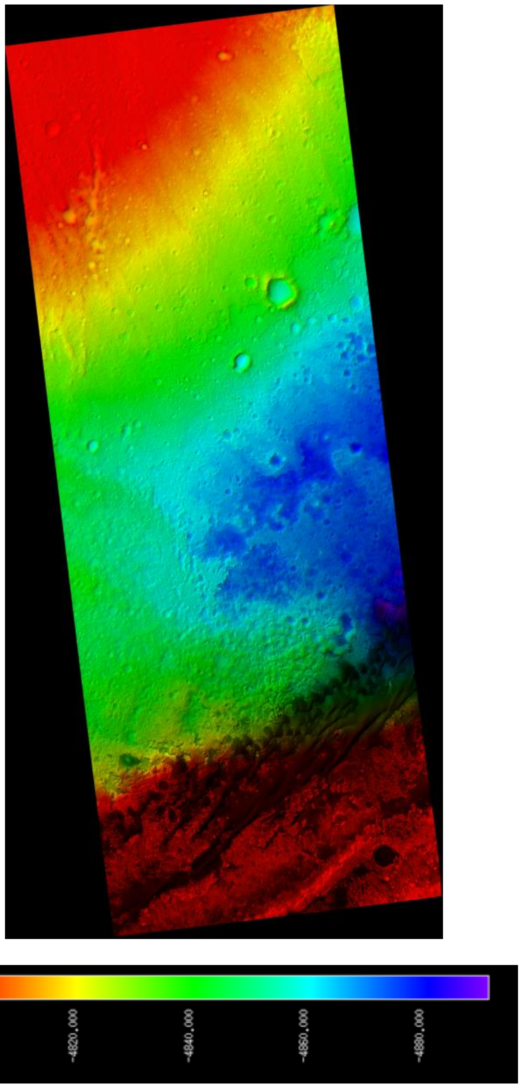


Figure 4-21. UCL HiRISE colour-coded DTM mixed with HiRISE ORI.

An example of a colour-coded display of the HiRISE DTM and ORI is shown in Figure 4-21.

4.3.3 Contour lines

Contour lines should represent the general morphology of the terrain. These should follow around hills and should well coincide with the visible features in the ORI. Here the UCL CTX ORI is applied as a base map for all derived contour lines. Hence, any shift in the co-registration between the ORI and the data set that is used for the contour lines could be visible.

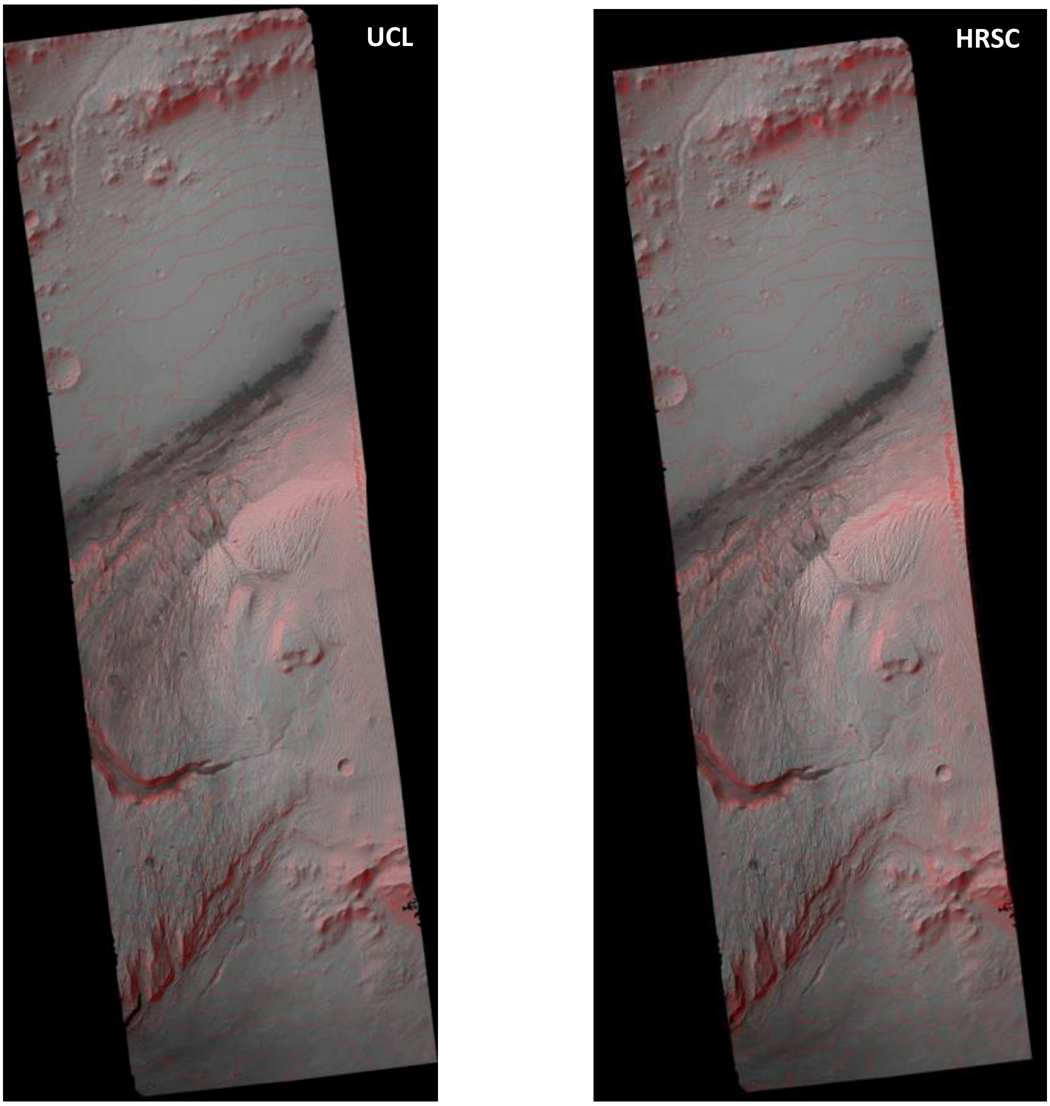


Figure 4-22: Comparison of contour lines and CTX ORI. Left contour lines computed from UCL CTX DTM. Right contour lines computed from HRSC DTM covering this area. Both have 50 m spacing between the contour lines.

The left display in Figure 4-22 shows the contour lines of the UCL DTM over the provided CTX ORI. These are well defined in craters and peaks or hills. Likewise, contour lines are continuous and plausible in smoother areas and follow well along valleys and shallow river beds.

The right display of Figure 4-22 shows in comparison the HRSC contour lines on the CTX ORI delivered by UCL. Here the contour lines are well defined along hill slopes and around peaks. Prominent features like hills, craters and slopes are well represented with the contour lines and are at the correct location. The HRSC data set lacks details over the flat areas north of the hills represented by the small nests of contour lines indicating a rather undulating area than a flat terrain.

The left display in Figure 4-23 shows the contour lines of the UoS DTM. These are well defined along slopes or hills and small peaks. Also along outflow channels a distinction can be made. In smooth and flat areas the lines become less defined and appear noisy though following the terrain.

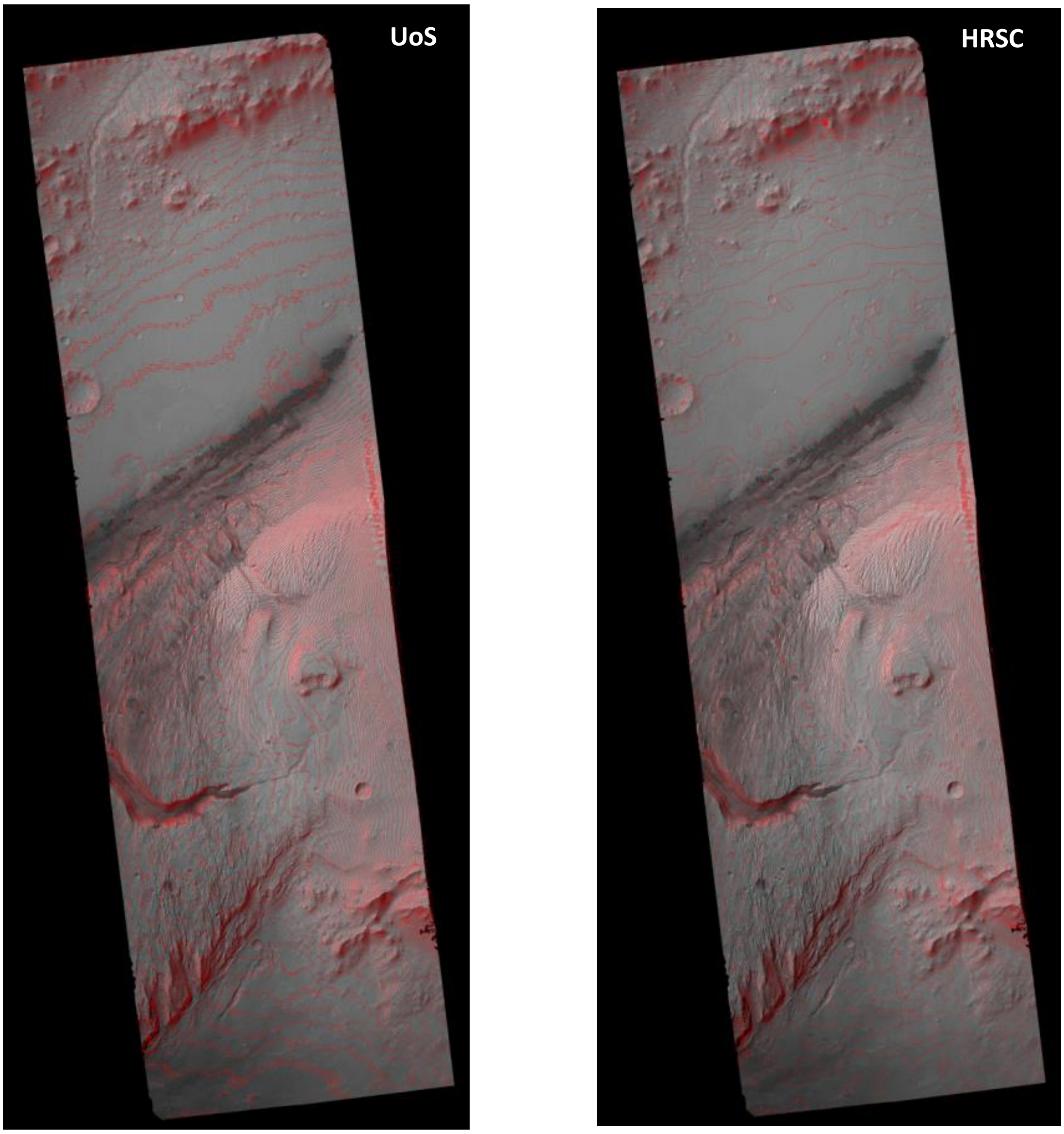


Figure 4-23: Comparison of contour lines and CTX ORI. Left contour lines computed from UoS CTX DTM. Right contour lines computed from HRSC DTM covering this area. Both have 50 m spacing between the contour lines.

4.3.4 Measurement of smallest visible crater

Visible crater like depressions in the DTM were identified and marked. Subsequently, these features in the DTM were identified in the ORI. Their diameter was then determined from the ORI information. This yields a qualitative assessment estimate of effective resolution. Strong smoothing of a DTM will lower that resolution. Examples of identified craters in the DTMs are shown in Figure 4-24 for both UCL and UoS DTMs.

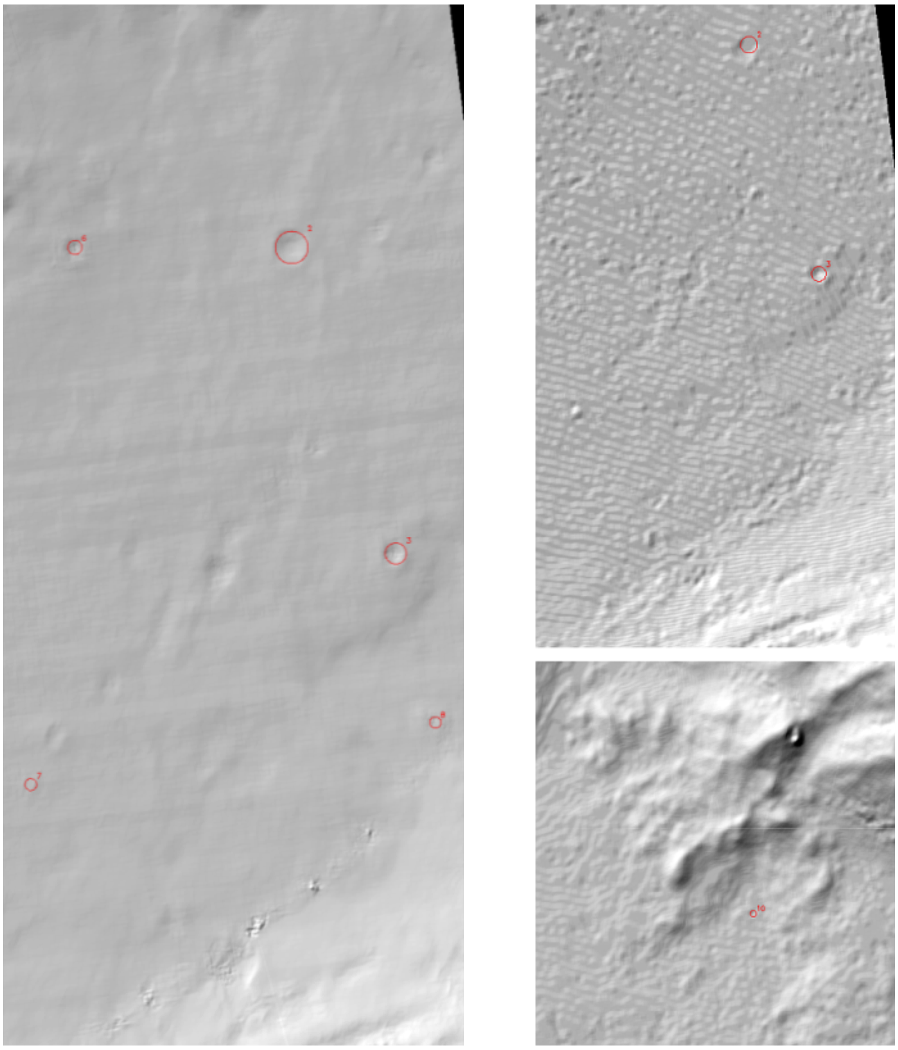


Figure 4-24: Cut outs of the MSL DTMs. Left the UCL product, right the UoS product. Some of the identified craters are marked.

4.3.5 Statistical measures

Table 4-6 and Table 4-7 show results of the statistical data analysis for the CTX MSL DTM from UCL and UoS. As described above, the HRSC DTM was resampled to fit to the data to be validated. Due to the different resolutions delivered between UCL and UoS, there is a discrepancy in the number of pixel elements evaluated. The resampling of the HRSC DTM causes only a slight change in the statistics (cf. 2nd column of both tables).

The UCL DTM (Table 4-6) has a minimum that is much higher in elevation in comparison to the HRSC DTM. However, since the average height value is comparable with the HRSC DTM value and differs by only 2 meters, it is assumed that this difference in minimum height value can be attributed to outliers in either of the data sets. A similar effect can be seen for the maximum DTM values. A similar cause for the differences between the DTMs as for the minimum heights is considered.

The observed standard deviation for the UCL CTX DTM is higher compared to the HRSC DTM. This could be due to the pattern observed that introduces additional noise to the scene. Another source for the higher standard deviation could be the increased detail of the CTX DTM in comparison to HRSC leading to many variations of the same order of magnitude.

Table 4-6: Statistical data of UCL MSL DTM

	HRSC DTM	UCL DTM	HRSC – UCL DTM
Number of Elements:	7072512	7072512	7072480
Minimum [m]:	-5339.23	-4983.46	-499.283
Maximum [m]:	-993.202	-1000.06	691.821
Height range [m]:	4346.028	3983.4	1191.104
Average DN Value [m]:	-3623.88	-3625.72	1.838
Standard Deviation [m]:	946.427	950.700	49.105

The UoS DTM for the MSL landing site area (Table 4-7) shows very similar statistical data in comparison to the UCL statistical data when looking at the maxima, minima and height range. Though the average height/DN value is larger than the reference height from the HRSC by 175 meters indicating that there is a height offset whereas the UoS DTM is located higher than the HRSC DTM.

Table 4-7: Statistical data of UoS MSL DTM

	HRSC DTM	UoS DTM	HRSC – UoS DTM
Number of Elements:	4011309	4011309	4011309
Minimum:	-5339.97	-4810.84	-680.760
Maximum:	-909.96	-735.67	519.560
Height range [m]:	4430.01	4075.17	1200.320
Average DN Value:	-3616.79	-3440.37	-176.415
Standard Deviation:	957.845	958.532	49.716

An assessment was also carried out of the HiRISE DTM compared with the one from CTX. This is shown in Table 4-8. HiRISE and coincident CTX DTMs for the MSL test site. and displays a very small bias (≤0.5m) and standard deviation of 5m

Table 4-8. HiRISE and coincident CTX DTMs for the MSL test site.

	CTX DTM	HiRISE DTM	CTX – HiRISE DTM
Number of Elements:	141,207,925	141,207,925	141,201,637
Height range [m]:	379.01	404.49	128.277
Average Height [m]:	-4,813.33	-4,812.86	-0.464
Standard Deviation [m]:	61.255	64.634	5.001

4.4 *Effective Resolution of the DTMs*

The provided DTMs carry metadata information stating the chosen pixel resolution of the data set. This represents the area that a pixel covers on the ground (cf. Table 2-1). However, this pixel resolution can significantly deviate from the effective resolution that provides an indicator what size of features are identifiable in the data set with confidence.

To derive a number for the effective resolution, craters in the UCL CTX ORI were identified and measured and counted according to their crater size. Subsequently the same craters were identified in the shaded DTM data and, if recognizable, counted into different classes of crater diameters. However, the derived numbers are merely an indication of the effective resolution. This is due to the paucity of craters in the landing site areas which is usually an engineering constraint for planetary mission due to safety concerns.

The MSL landing site area was the only test site of the three considered sites of this report, to provide sufficient distribution in the crater diameter.

In Figure 4-25 the graph shows the percentage of craters recognizable in the respective DTM with the reference of the crater counts in the ORI. It becomes clear that only craters in the diameter range between 400 to 450 meters can be recognized in the UCL DTM with a confidence of 50%. The same is basically true for the UoS DTM though in the next higher crater diameter class the confidence decreases for the UoS data to a confidence level of only 30%. Hence, only crater detections of craters with diameters larger than 500 meters can be trusted in the UoS DTM.

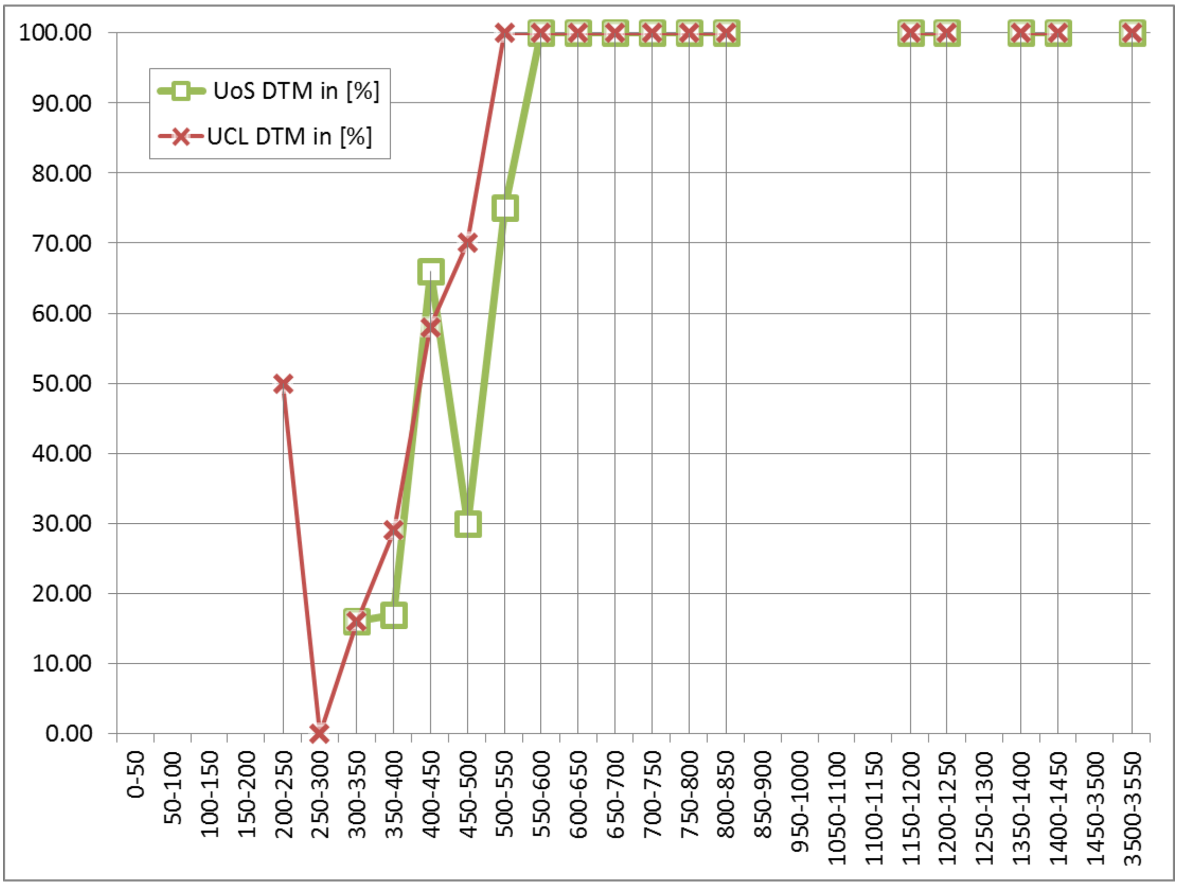


Figure 4-25: Effective resolution as observed in the provided CTX DTMs for the MSL landing site area.

For both the delivered CTX DTMs of the MSL landing site region the effective resolution differs significantly to the pixel resolution the DTMs were delivered in. In a very optimal scenario one would expect the effective resolution in the order of 2 to 3 times the pixel resolutions. In the test cases here the factors are in the range of 20 (UoS) to 22 (UCL).

5 Summary

Summarizing the validation of the DTM products delivered by UCL and UoS one can conclude that the quality of the DTM

- data sets varies strongly between the different test sites reflecting the quality of the input stereo-pair of images,
- varies strongly depending on the pipeline applied to derive the products.

The former can be caused by many factors. One is the type of landscape that was observed, another could be the quality of the input data varying between the different landing site areas. It is assumed that both groups used the same input data for a certain landing site such that any differences in quality for one landing site between the providers DTMs can be attributed to the processing rather than to any other effect.

Overall, almost every delivered DTM shows signs of systematic artifacts that are – due to the different nature of these artifacts when comparing the results of UCL and UoS – likely caused by the specific processing chain. The artifacts add noise to the resulting terrain models that UCL apparently counteracted by smoothing the data. This, however, decreases the effective resolution of the data set making it more difficult to observe small craters. The latter are difficult to identify in the shaded DTM data anyhow due to the above mentioned noise and artifacts. Widespread noise artefacts obviously limit the effective resolution of a DTM, even if some small-scale morphological features of similar dimensions appear to represented as well. Therefore, the approach of UCL to apply filtering is justified. A reduction of nominal grid scale according to the smoothing characteristics of the filtering would, however, be suggested. This is corroborated by our analysis of crater detection probability in the DTM, which led us to the conclusion that the numerical spatial resolution (grid spacing) of the DTMs could be reduced by a factor of 5-10 without loss in effective resolution.

This assertion is contested by UCL as they do not accept that the method employed by Heipke et al (2007) has any scientific justification. A much more thorough and rigorous method is that proposed by Kirk et al. (2003) to examine bidirectional slopes. However, there is no general consensus regarding this important matter.

The HiRISE DTMs are similarly variable in quality with the MSL being the best and the MER-B the worst with the MER-A being somewhat in between.

The MSL landing site area DTMs show the highest quality among the delivered data sets. These are well defined data sets with an acceptable level of noise. The MER-A landing site are DTMs are in the medium range with respect to quality, whereas the UoS DTM shows a global distortion of the surface reconstruction with a large number of artifacts in the most interesting area of the Columbia Hills.

The MER-B landing site area DTMs have the data with the poorest inputs and results. Here one comes to the conclusion that the landscape type is of significant influence. MER-B landing site area is a flat dune covered area, whereas the MER-A region contains some craters and surface variation, and the Gale crater – MSL landing site – provides a well-structured landscape providing many anchor points for matching algorithms.

References

Gwinner, K., Jaumann, R., Hauber, E., Hoffmann, H., Heipke, C., Oberst, J., Neukum, G., Ansan, V., Bostelmann, J., Dumke, A., Elgner, S., Erkeling, G., Fueten, F., Hiesinger, H., Hoekzema, N.M., Kersten, E., Loizeau, D., Matz, K.D., McGuire, P.C., Mertens, V., Michael, G., Pasewaldt, A., Pinet, P., Preusker, F., Reiss, D., Roatsch, T., Schmidt, R., Scholten, F., Spiegel, M., Stesky, R., Tirsch, D., van Gasselt, S., Walter, S., Wählisch, M., Willner, K., 2016. The High Resolution Stereo Camera (HRSC) of Mars Express and its approach to science analysis and mapping for Mars and its satellites. Planetary and Space Science 126, 93-138.

Gwinner, K., Scholten, F., Spiegel, M., Schmidt, R., Giese, B., Oberst, J., Heipke, C., Jaumann, R., Neukum, G., 2009. Derivation and Validation of High-Resolution Digital Terrain Models from Mars Express HRSC-Data. PE&RS 75, 1127-1142.

Heipke, C., Oberst, J., Albertz, J., Attwenger, M., Dorninger, P., Dorrer, E., Ewe, M., Gehrke, S., Gwinner, K., Hirschmüller, H., Kim, J.R., Kirk, R.L., Mayer, H., Muller, J.-P., Rengarajan, R., Rentsch, M., Schmidt, R., Scholten, F., Shan, J., Spiegel, M., Wählisch, M., Neukum, G., Team, t.H.C.-I., 2007. Evaluating planetary digital terrain models--The HRSC DTM test. Planetary and Space Science 55, 2173-2191.

Jaumann, R., Neukum, G., Behnke, T., Duxbury, T.C., Eichentopf, K., Flohrer, J., Gasselt, S.v., Giese, B., Gwinner, K., Hauber, E., Hoffmann, H., Hoffmeister, A., Köhler, U., Matz, K.-D., McCord, T.B., Mertens, V., Oberst, J., Pischel, R., Reiss, D., Ress, E., Roatsch, T., Saiger, P., Scholten, F., Schwarz, G., Stephan, K., Wählisch, M., 2007. The high-resolution stereo camera (HRSC) experiment on Mars Express: Instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. Planetary and Space Science 55, 928-952.

Kim, J.-R., 2010. Evaluation of Mojave topographic products, and explanation of production methods, in: Goddard, K., Gupta, S. (Eds.), p. 6.

Kim, J.R., Muller, J.P., 2009a. Multi-resolution topographic data extraction from Martian stereo imagery. Planetary and Space Science 57, 2095-2112.

Kim, J.R., Muller, J.P., 2009b. Multi-resolution topographic data extraction from Martian stereo imagery. Planet Space Sci 57, 2095-2112.

Malin, M.C., Bell, J.F., Cantor, B.A., Caplinger, M.A., Calvin, W.M., Clancy, R.T., Edgett, K.S., Edwards, L., Haberle, R.M., James, P.B., Lee, S.W., Ravine, M.A., Thomas, P.C., Wolff, M.J., 2007. Context Camera Investigation on board the Mars Reconnaissance Orbiter. Journal of Geophysical Research: Planets 112, E05S04.

Mattson, S., Boyd, A., Kirk, R.L., Cook, D.A., Howington-Kraus, E., 2009. HiJACK: Correcting spacecraft jitter in HiRISE images of Mars, European Planetary Science Congress 2009, p. 604.
McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., Weitz, C.M., 2007. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). Journal of Geophysical Research 112, E05S02.

Neumann, G.A., Abshire, J.B., Aharonson, O., Garvin, J.B., Sun, X., Zuber, M.T., 2003. Mars Orbiter Laser Altimeter pulse width measurements and footprint-scale roughness. Geophysical Research Letters 30, 1561.

Neumann, G.A., Rowlands, D.D., Lemoine, F.G., Smith, D.E., Zuber, M.T., 2001. Crossover analysis of Mars Orbiter Laser Altimeter data. J Geophys Res-Planet 106, 23753-23768.

Smith, D.E., Zuber, M.T., Neumann, G.A., Guinness, E.A., Slavney, S., 2003. Mars Global Surveyor Laser Altimeter Mission Experiment Gridded Data Record.

6 Annex : Self-validation of UoS CTX and HiRISE products

UoS conducted their own validation work for some CTX and HiRISE products which were produced by the UoS in-house processing chain. It was conducted over a few locations using mainly MOLA track profiles. Two cases are described here.

6.1 Test site 1 : Elysium

Over Elysium, UoS constructed a CTX DTM (12m) and HIRISE ortho images and DTMs (1m). At first glance, the geodetic accuracies of CTX DTM is very high, with up to only few metres error level as shown in figure 6-1 (a) and Table 1. Since the matching blunders were well regulated especially over the hydrological channel bed, it is expected that the hydraulic analysis is conducted very stably with the CTX DTM. The only problem found with CTX DTM, is that there is a wave pattern over the stereo DTM which is originated from the oscillation of the sensor pointing as described in Kirk et al. (2008). The application of “spicefit” program which was developed to reduce the noise associated with the instrument pointing in the pre processing stage using USGS ISIS removed the high frequency oscillation components of sensor points but didn’t address the slow varying effects

HiRISE stereo analysis produced a visually error free DTM (Figure 6-1 (b)) but the quantitative comparison with MOLA identified the disparity in terms of the geodetic control. It is confirmed in the relatively noticeable root squares mean values of the HiRISE-MOLA comparison shown in Table 6-1. Considering the indispensible error originated with the spatial resolution difference of MOLA footprint (75-150m) and the grid size of the HiRISE DTM, the large standard deviation value in HIRISE-MOLA comparison is somewhat understandable. However, under manual inspection and the DTM track profiles, the horizontal shift is less than 100m and a few metres’ vertical offsets compared with MOLA were founded. Thus, to evaluate the influence of the geodetic offset between HIRISE DTM and MOLA, we applied a secondary control procedure for HiRISE DTM and MOLA using surface matching developed based on a seven-parameter 3D conformal coordinate transformation (Lin et al., 2010). By solving the transformation parameters through iterative minimisation of surface differences, the best fit of the two terrain surfaces was determined (see track profiles in Figure 6-1. (b) for the before and after surface matching). An accurate co-registration of the two surfaces was then achieved once the transformation was applied. It is interesting to observe whether the surface matched DTM change the output of scientific interpretation

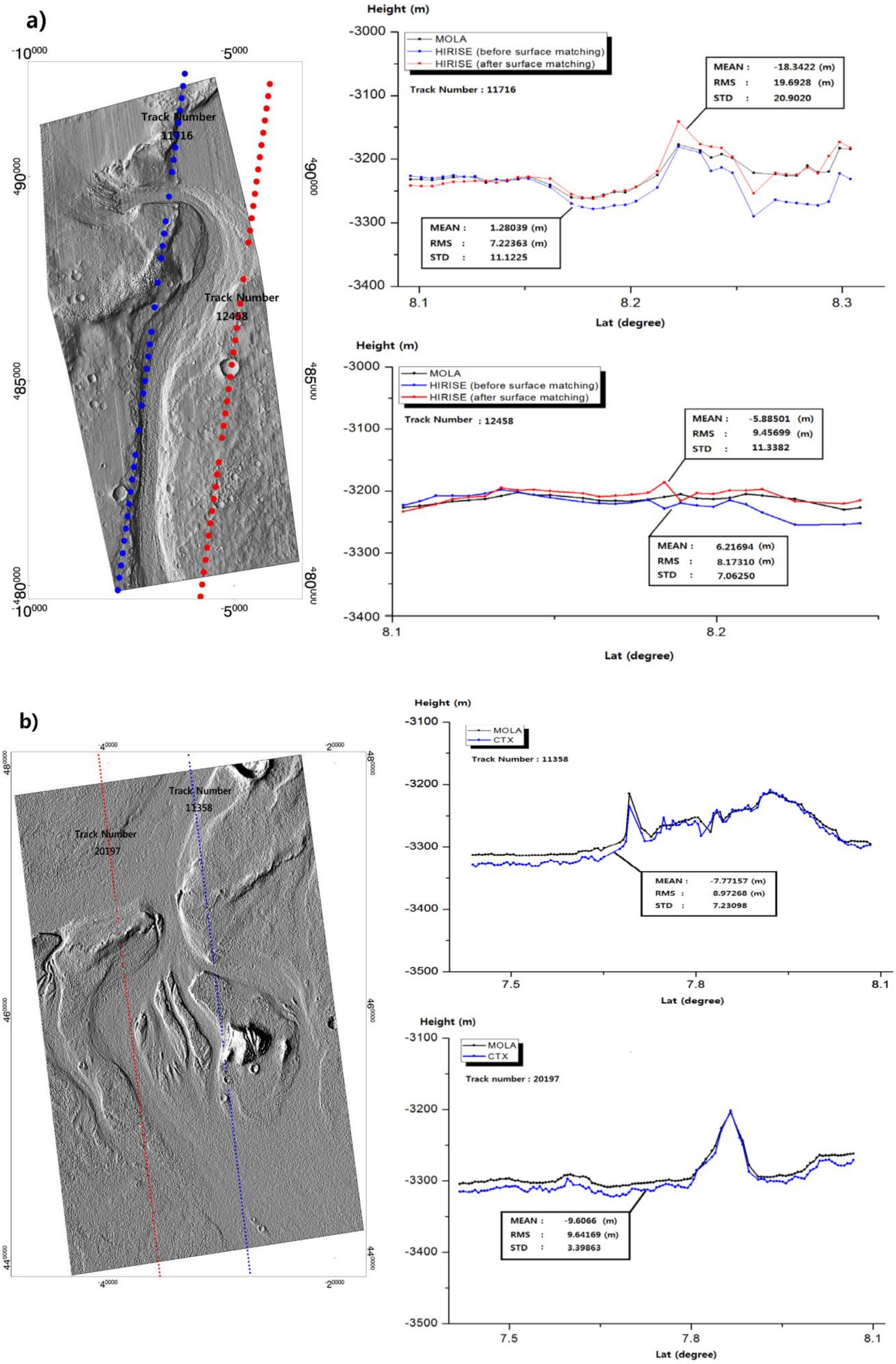


Figure 6-1: MOLA track profiles over HiRISE (a) and CTX (b). Note the difference between MOLA track profiles before and after surface matching over HiRISE DTM.

Table 6-1: Comparison datasets and their properties.

	HRSC-MOLA (m) (109095 MOLA points)	CTX-MOLA (m) (2342 MOLA Points)	HiRISE-MOLA (m) (138 MOLA points)	
			Without surface matching	With surface matching
Mean height difference	2.109	0.506	16.203	-2.244
root Squared mean differences	13.669	6.933	17.732	6.764
Standard deviations of differences	28.783	8.694	18.956	9.199
Maximum height difference	401.060	29.7996	69.059	32.499
Minimum height difference	-1096.12	-44.442	-10.836	-39.865

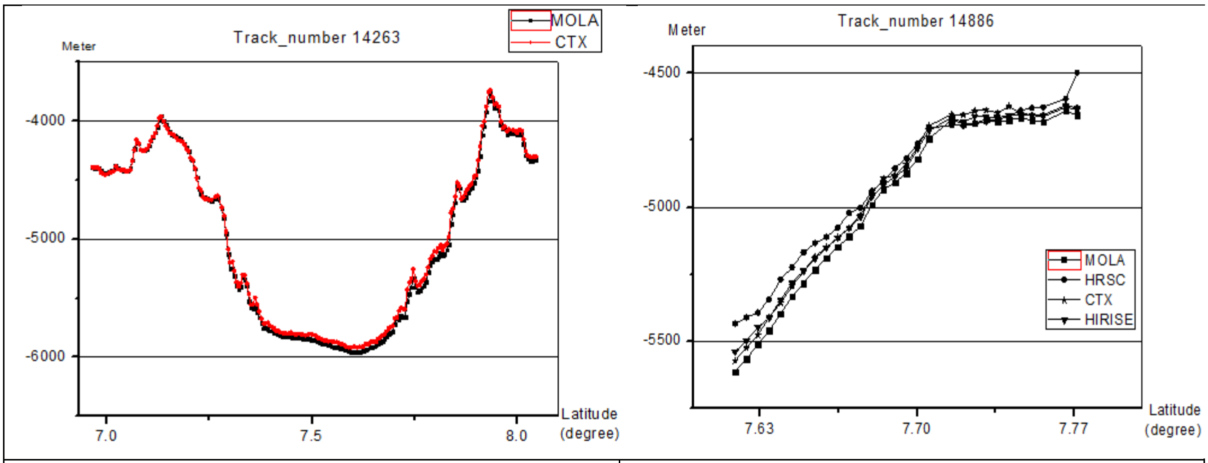
6.2 Test site 2 : Mojave crater

The data sets employed in this area are follows

1. ~1 m resolution HiRISE DTM constructed from HiRISE stereo pair images PSP_002167_1880 and PSP_001481_1875.
2. 10 m resolution CTX DTM constructed from CX stereo pair P19_008496_1875 and P21_009076_1875.
3. ~25 m resolution HRSC DTM constructed from the HRSC image h2009_01_002.
4. Mars Orbiter Laser Altimeter (MOLA) Precision Experimental Data Records (PEDR) track data for the North Eastern area of the ejecta blanket. The following tracks were used: 18713L.B, 16866L.B and 14883L.B. These give spot elevations projected over a ≈180m footprint of a known coordinate to an accuracy of ~ 1 m, and are spaced at 300 m intervals along a track.

Due to the high signal to noise ratio and relatively high horizontal instantaneous field of view together with an updated stereo matcher (Kim and Muller, 2009b), the CTX and HiRISE topographic products produced for Mojave crater demonstrate highly reliable quality (Kim, 2010). To determine the accuracy of the topographic products, the relevant MOLA PEDR tracks (corrected for bad orbits and biases (Neumann et al., 2001)) were employed to calculate the difference between MOLA heights and the gridded elevation from the HRSC, CTX and HiRISE DTMs. Figure 6-2 (a) shows a comparison between MOLA and CTX data across the entire crater (using MOLA track 14263), and Figure 6-2 (b) shows a comparison between MOLA, HRSC, CTX and HiRISE data using the MOLA PEDR track 14886. The data sets are very well matched, showing excellent accuracy for the topographic products (Table 6-2). It should be noted the there is a large difference between the MOLA footprint size and the spatial grid of the stereo DTMs so that little discrepancy between MOLA-CTX, HiRISE DTMs can be interpreted as the effect of spatial resolutions difference of the DTMs rather than the inaccuracy of the photogrammetric control.

The details on spatial resolution effects of various Martian DTMs are described in Kim and Muller (2009) and Kim and Muller (2008) in depth.



(a) MOLA and CTX comparison | (b) MOLA, HRSC, CTX and HiRISE comparison

Figure 6-2: MOLA track profiles over CTX (a) and HiRISE (b).

Table 6-2: Comparison datasets and their properties

	Mean	Stddev
MOLA-CTX	mean : 0.888m	29.468m
MOLA(78 points)-HIRISE	8.043m	24.432m

Annex References

Kirk, R. L., Howington-Kraus, E., Rosiek, M. R., Anderson, J. A., Archinal, B. A., Becker, K. J., ... & McEwen, A. S. (2008). Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: Meter-scale slopes of candidate Phoenix landing sites. *Journal of Geophysical Research*, *113*(E3), E00A24.

Kim, J.R., Muller, J.P., 2009. Multi-resolution topographic data extraction from Martian stereo imagery. *Planetary and Space Science* 57, 2095-2112.

Kim, J.R., Lin, S.H., Hong, J.W., Kim, Y.H., & Park, J. G., (2012). Implementation of Martian virtual reality environment using very high-resolution stereo topographic data. *Computer and Geoscience*, 44, 184-195.

Lin, S.Y., Muller, J-P., Mills, J.P., & Miller, P.E., (2010). An assessment of surface matching for the automated co-registration of MOLA, HRSC and HiRISE DTMs. *Earth and Planetary Science Letter*, 294, 520-533 (2010)

Neumann, G.A., Rowlands, D.D., Lemoine, F.G., Smith, D.E., & Zuber, M.T., (2001). Crossover analysis of Mars Orbiter Laser Altimeter data. *Journal of Geophysical Research.* 106(E10), 23753-23768