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HRSC-CTX-HIRISE CO-REGISTERED DIGITAL TERRAIN MODELS AND TERRAIN-CORRECTED IMAGES OF OXIA PLANUM OF MARS

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1. INTRODUCTION

Large area, high-resolution, three-Dimensional (3D) mapping of the Martian surface is not only essential for performing key science investigations of the generation and evolution of the planet's surface, but also critical for supporting existing and future surface robotic missions as well as human exploration. Over the past 20 years, 3D mapping of the Martian surface has only been done for larger areas with lower-resolution data, or for small areas with higher-resolution data.

The large area lower-resolution 3D mapping work usually uses the ESA Mars Express's High Resolution Stereo Camera (HRSC) data at 12.5–50m/pixel producing photogrammetric digital terrain models (DTMs) at 50–150m/pixel or uses the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) data at 6m/pixel producing DTMs at 18–24m/pixel where such serendipitous stereo coverage exists and the images are of a suitable quality to process stereo photogrammetrically.

On the other hand, small area high-resolution 3D mapping work usually employs the MRO High Resolution Imaging Science Experiment (HiRISE) data at 0.25–0.5m/pixel producing DTMs at 0.75–2m/pixel using photogrammetry or DTMs at 0.25–0.5m/pixel using photoclinometry, or uses the ExoMars Trace Gas Orbiter (TGO) Colour and Stereo Surface Imaging System (CaSSIS) data at 4–6m/pixel producing DTMs at 12–18m/pixel using photogrammetry or at 4m/pixel using photoclinometry (at the pixel-level) or at 1m/pixel using super-resolution restoration assisted photoclinometry (at the sub-pixel level) (***Tao et al., 2021a***).

The limitations of having to trade-off between "large area" and "high-resolution", for Mars 3D mapping is a consequence of three different aspects. Firstly, lower-resolution data such as HRSC has better stereo coverage as it is inherently a stereo mapping instrument, whereas the main high-resolution data to date (HiRISE) is only capable of targeted stereo. Secondly, the photogrammetry and photoclinometry processes are complex and subject to different errors (or artefacts) at each of their different processing stages, which require specialist expertise to deal with these complexities in order to produce high-quality DTM products, especially over large areas. Thirdly, the expensive computational cost from existing photogrammetry and photoclinometry pipelines makes it extremely difficult to achieve large area high-resolution coverage. Other UCL DTM datasets published here have employed the CASP-GO (***Tao et al., 2018***) to produce extensive HRSC DTM datasets (***Tao et al., 2021b***).

In this work, we experiment with a previously developed single-input-image fast DTM surface modelling system, called MADNet (Multi-scale generative Adversarial u-net with Dense convolutional and up-projection blocks) (***Tao et al., RS, 2021c***), exploring large area high-resolution DTM production using a set of co-registered HRSC-CTX-HiRISE images that are co-aligned with the global reference DTM from the Mars Global Surveyor's Mars Orbiter Laser Altimeter (MOLA) (***Tao et al., RS, 2021d***). In contrast with traditional photogrammetric methods, where two overlapping images (with a suitable stereo angle, typically ≥8°) are used as inputs to derive the DTM, MADNet requires only a single image as input to derive a DTM, firstly in relative values (normalised), and then by using a referencing coarse resolution DTM (e.g., the globally available MOLA DTM) to produce the final DTM product. It should be noted that the referencing basemap DTM is usually sourced from photogrammetric methods because the initial surface heights, triangulated from the relative image disparities, are generally considered imprecise and are required to be corrected using a reference DTM (typically being the downsampled 463m/pixel MOLA DTM for Mars). The above differences are illustrated in **Figure 1**, where we show a simplified flow diagram of the photogrammetric DTM pipeline and the deep learning-based single-image DTM pipeline (e.g., MADNet). See (***Tao et al., RS, 2021c***) for more details.

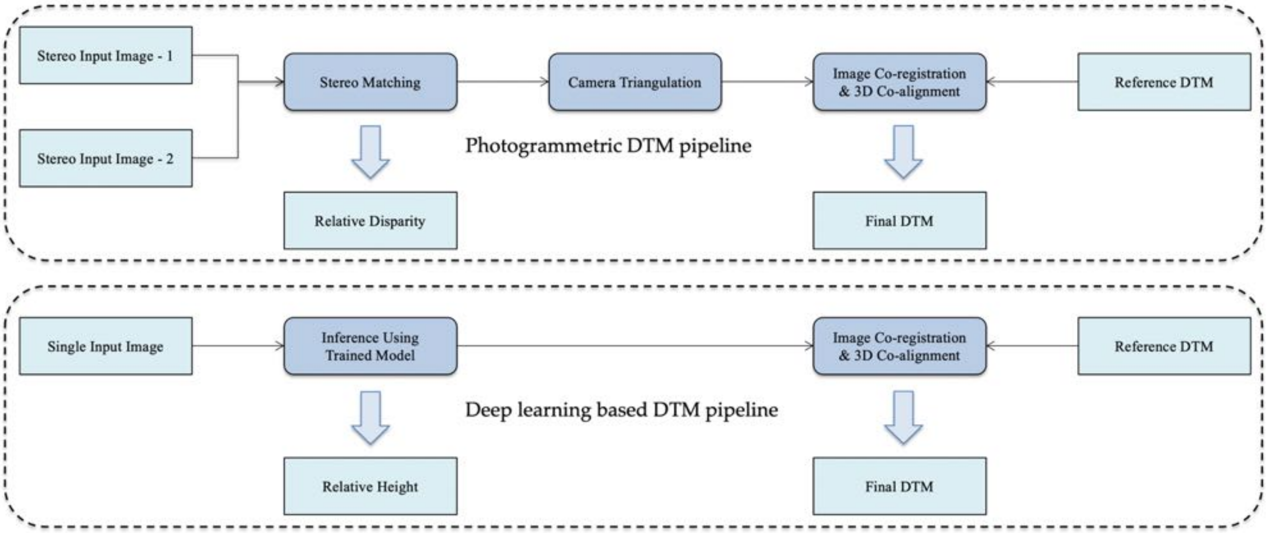

*Figure 1. Illustration of the major differences between the photogrammetric DTM pipeline and the deep learning-based single-image DTM pipeline (e.g., MADNet) discussed here. Taken from (**Tao et al., RS, 2021d**).*

1.1 Instrument and Datasets

We focus on the Oxia Planum area, where the joint European Space Agency (ESA) and Russian Roscosmos ExoMars mission will land the ESA "Rosalind Franklin" rover and the Roscosmos landing platform "Kazachok" in 2023. Large area high-resolution DTM mosaics, covering the 3-sigma landing ellipses, are produced here at 25m/pixel for HRSC, 12m/pixel for CTX, and at 50cm/pixel for HiRISE. Cascaded 3D co-alignments (HRSC-to-MOLA, CTX-to-HRSC, and HiRISE-to-CTX) have been achieved (ibid.) to guarantee precise global congruence with respect to MOLA. Part of this area has been used for the Jet Propulsion Laboratory webGIS (web based Geographic Information System) called MMGIS (Multi-Mission Geographic Information System) to assist the ExoMars team's geological characterisation of the area.

In this work, a total of 12 CTX images (6 serendipitous pairs) and 44 HiRISE images are used (both are manually selected using a list from the PDS product coverage shapefiles to cover the 3-sigma landing ellipses and partially the ExoMars team's geological characterisation area. The input HiRISE images are manually selected for quality, while keeping sufficient overlaps within neighbouring scenes in order to produce a single uniform quality and gap-free DTM mosaic. The 25cm/pixel images have a priority over 50cm/pixel images if both cover the same area. Some HiRISE images that contain severe framelet-stitching artefacts or missing data are excluded. New images are also checked to fill remaining DTM gaps at the end of the process. It should be noted that there are many more images that exist then are available other than the selected CTX and HiRISE images for this work.

An overview of the area covered, and the input MOLA-HRSC-CTX-HiRISE datasets, are shown in **Figure 2**. The yellow boxes in **Figure 2** represent the coverage of the available HiRISE images (up until NASA's last released images on 09 June 2021) within the 3-sigma landing ellipses, where the yellow boxes with hatched fill are HiRISE images with off-nadir counterparts and the plain yellow boxes are HiRISE images without any repeat observations (i.e., only single views are available). As the proposed method only requires single images as inputs, the 3D mapping area for HiRISE can be greatly enlarged to cover other areas without any targeted or serendipitous observations being available.

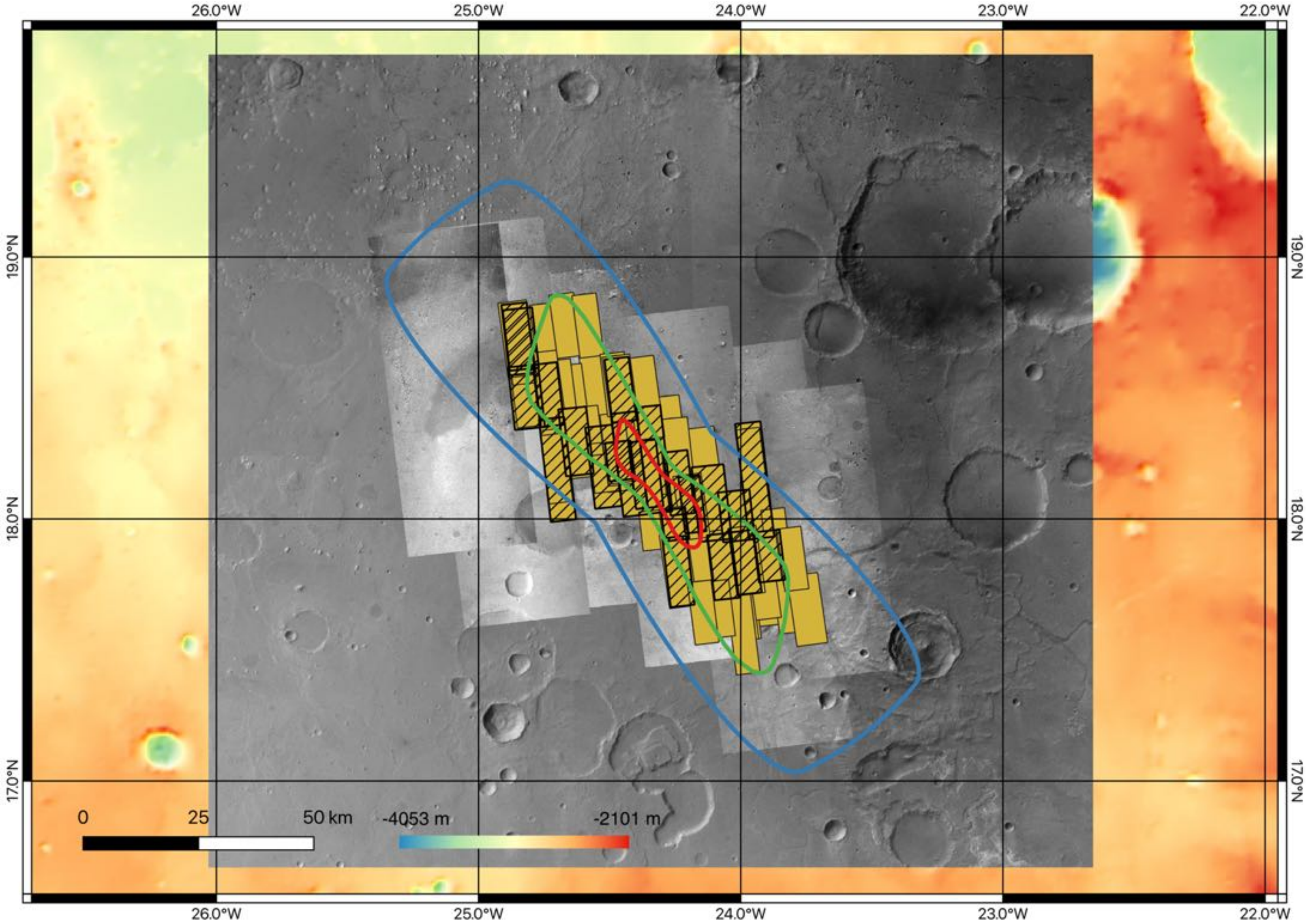

*Figure 2. An overview of the proposed 3D mapping area at Oxia Planum (centred at 18.239°N, 24.368°W), showing the ESA Rosalind Franklin rover 2022 1-sigma (red) and 3-sigma (green) landing ellipse areas and the ExoMars team's geological characterisation area (blue). Shown in the background are the co-registered input datasets of MOLA DTM (colourised and hill-shaded), cropped HRSC MC-11W level 5 ORI greyscale mosaic, CTX ORI mosaic, and HiRISE image footprints (in yellow; with hatched outlines referring to those available with off-nadir stereo; the footprints are relevant to the NASA release data of 09 June 2021). Taken from (**Tao et al., RS, 2021**d)*

1.2 Abbreviations and Acronyms

DTM	Digital Terrain Model
DUG	Data User Guide
ESA	European Space Agency
GIS	Geographic Information System
HRSC	High-Resolution Stereo Camera
CTX	Context camera
HiRISE	High Resolution Imaging Science Experiments
MOLA	Mars Orbiter Laser Altimeter

NASA	National Aeronautics and Space Administration (United States)
ORI	OrthoRectified Images
PSA	Planetary Science Archive
UCL	University College London

1.3 Reference and Applicable Documents

Tao, Y.; Muller, J. P.; Sidiropoulos, P.; Xiong, S.-T.; Putri, A. R. D.; Walter, S. H. G.; Veitch-Michaelis, J.; Yershov, V. Massive Stereo-based DTM Production for Mars on Cloud Computers. *Planetary Space Science* **2018**, *154*, 30–58.doi: 10.1016/j.pss.2018.02.012

Tao, Y.; Michael, G.; Muller, J.-P.; Conway, S. J.; Putri, A. R. D. Seamless 3D Image Mapping and Mosaicing of Valles Marineris on Mars Using Orbital HRSC Stereo and Panchromatic Images. *Remote Sensing* **2021a**, *13*, 1385.doi: 10.3390/rs13071385

Tao, Y.; Conway, S. J.; Muller, J.-P.; Putri, A. R. D.; Thomas, N.; Cremonese, G. Single Image Super-Resolution Restoration of TGO CaSSIS Colour Images: Demonstration with Perseverance Rover Landing Site and Mars Science Targets. *Remote Sensing* **2021b**, *13*, 1777. doi: 10.3390/rs13091777

Tao, Y.; Xiong, S.; Conway, S.J.; Muller, J.-P.; Guimpier, A.; Fawdon, P.; Thomas, N.; Cremonese, G. Rapid Single Image-Based DTM Estimation from ExoMars TGO CaSSIS Images Using Generative Adversarial U-Nets. *Remote Sens.* **2021c**, *13*, 2877. https://doi.org/10.3390/rs13152877

Tao, Y.; Muller, J.-P.; Conway, S.J.; Xiong, S. Large Area High-Resolution 3D Mapping of Oxia Planum: The Landing Site for the ExoMars Rosalind Franklin Rover. *Remote Sens.* **2021d**, *13*, 3270. https://doi.org/10.3390/rs13163270

2. SCIENTIFIC OBJECTIVES

All results shown here are made for the Rosalind Franklin ExoMars 2022 rover's landing site at Oxia Planum. This site is a 200 km wide clay bearing plain centred on 18.239° N, 24.368° W (see **Figure 2**) inside the United States Geological Survey (USGS)'s Oxia Palus (MC-11) quadrangle of Mars. The landing site area straddles the dichotomy boundary of Mars, which separates the northern lowlands from the southern highlands. The site slopes towards the north and hosts mineralogical (iron-magnesium rich clay minerals) and geomorphological evidence of liquid water in the ancient past, which motivated the choice of this site for this mission whose principal objective is to search for potential biomarkers indicating past life on Mars.

2.1 Acknowledgements

Users are requested to acknowledge the dataset by mentioning it in any relevant figure captions and within acknowledgement within their publications to cite both the DOI of the dataset and the paper describing the processing system, assessment, and mosaic generation:

Tao, Y.; Muller, J.-P.; Conway, S.J.; Xiong, S. Large Area High-Resolution 3D Mapping of Oxia Planum: The Landing Site for the ExoMars Rosalind Franklin Rover. *Remote Sens.* **2021**, *13*, 3270. https://doi.org/10.3390/rs13163270

Tao, Y.; Xiong, S.; Conway, S.J.; Muller, J.-P.; Guimpier, A.; Fawdon, P.; Thomas, N.; Cremonese, G. Rapid Single Image-Based DTM Estimation from ExoMars TGO CaSSIS Images Using Generative Adversarial U-Nets. *Remote Sens.* **2021**, *13*, 2877. https://doi.org/10.3390/rs13152877

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3. DATA PRODUCT GENERATION

The processing core of this work is the MADNet deep learning based single-image DTM estimation system described in (***Tao et al., RS, 2021c***). MADNet is based on the Generative Adversarial Network (GAN) framework. In particular MADNet is based on a multi-scale relativistic GAN architecture, which was previously developed for image super-resolution tasks. MADNet operates by training a generative model for relative height prediction, and in an alternating manner, updating a discriminator model to distinguish the predicted heights from the normalised ground-truth heights.

The MADNet generator network uses a three-scale U-Net based architecture. Each of the three-scale U-Nets (the coarse-scale, intermediate-scale, and fine-scale) consists of a dense convolution block (DCB) based encoder arm and an up-projection block (UPB) based decoder arm. The fine-scale U-Net contains five stacks of convolutional layers, pooling layers, and DCBs to encode the input image into a feature tensor, which is then fed into five stacks of UPBs and convolutional layers with concatenations of the corresponding outputs of each pooling layer to decode the feature vectors into the output height map. The intermediate-scale and coarse-scale U-Nets take two times and four times downsampled input images and use four and three stacks of the convolution-pooling-DCB and UPB-convolution layers to reconstruct the height maps in two times and four times coarser scales, respectively.

Outputs from the three-scale U-Net networks are then merged with adaptive weights to reconstruct the final output height map (relative height). A simplified network architecture of the MADNet generator can be found in **Figure 3** for a detailed description (including the discriminator network), please refer to (***Tao et al., RS, 2021a***).

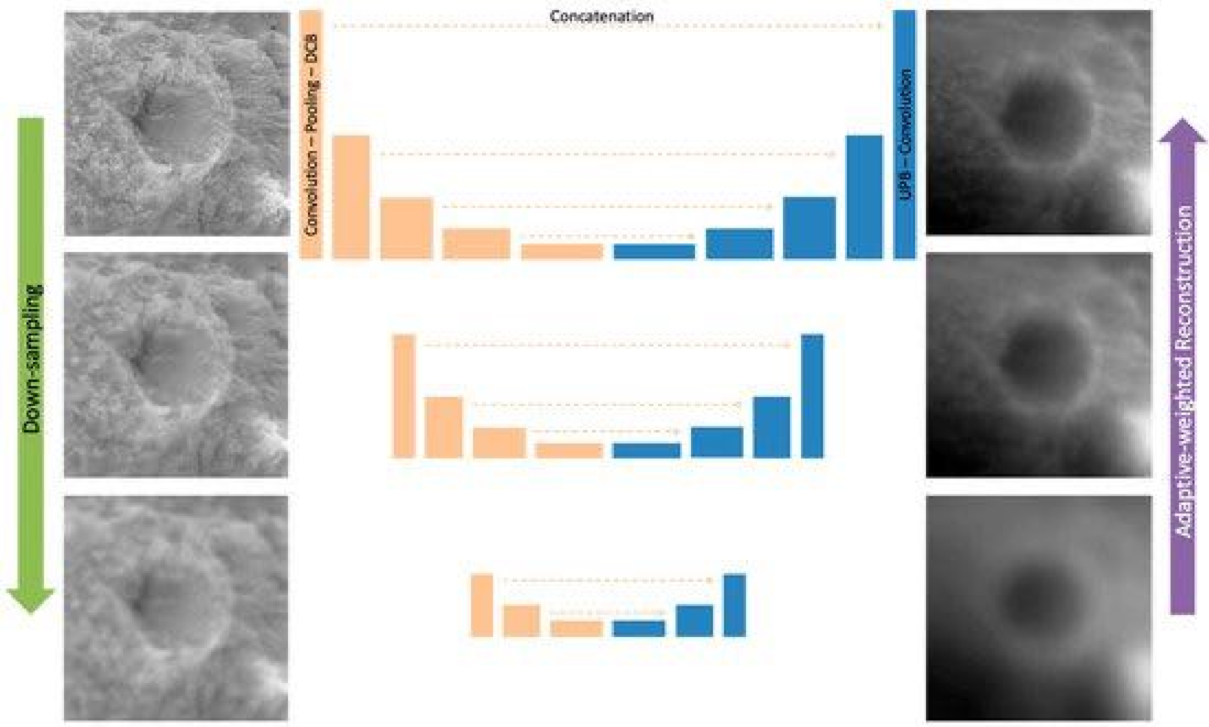

Figure 3. Overview of the MADNet generator network architecture. The input image has a size of 512 × 512 pixels and the final output height map has a size of 256 × 256 pixels in a relative value range of (0, 1).

In this work (***Tao et al., RS, 2021c***), MADNet is employed alongside 3D co-alignment and DTM mosaicing methods to produce co-aligned DTM mosaics using a set of co-registered

HRSC-CTX-HiRISE images over the landing site area. The overall processing chain of the work described here is shown in **Figure 4**.

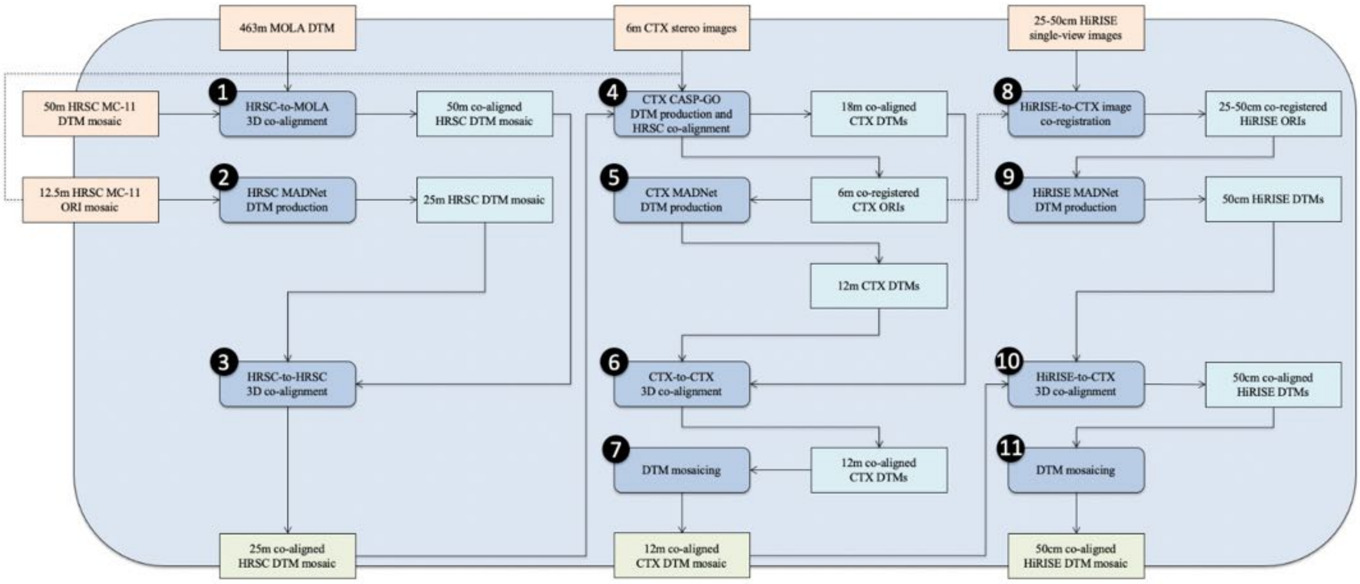

Figure 4. Overall processing chain of the large area multi-resolution (HRSC-CTX-HiRISE) 3D mapping work. Inputs are shown with the light orange boxes, intermediate products with the light blue boxes, and final outputs are shown with the light green boxes.

The inputs of the proposed large area multi-resolution 3D mapping work are the 463m/pixel MOLA areoid DTM (available at https://astrogeology.usgs.gov/search/details/Mars/GlobalSurveyor/MOLA/Mars_MGS_MOLA_DEM_mosaic_global_463m/cub), the 50m/pixel HRSC MC-11W (Mars Chart-11 West) level 5 DTM mosaic and 12.5m/pixel ORI mosaic (available at http://hrscteam.dlr.de/HMC30/MC11W/), the 6m/pixel CTX stereo-view images (accessible through the Arizona State University's Mars Image Explorer at http://viewer.mars.asu.edu/viewer/ctx), and the 25–50cm/pixel HiRISE single-view (monocular) images (available through the University of Arizona's HiRISE site at https://hirise-pds.lpl.arizona.edu/PDS/). The CTX and HiRISE image IDs that cover the landing site area were found through the product coverage shapefile site (https://ode.rsl.wustl.edu/mars/coverage/ODE_Mars_shapefile.html).

The overall processing chain includes 11 steps (labelled in **Figure 3**) and can be summarised as follows:

1) B-spline fitting based on 3D co-alignment of the input (cropped) HRSC MC-11W level 5 DTM mosaic with respect to the input MOLA DTM to obtain an intermediate 50m/pixel MOLA corrected HRSC DTM mosaic.
2) MADNet DTM production, using the cropped HRSC MC-11W level 5 ORI mosaic as input to produce an intermediate 25m/pixel HRSC DTM mosaic.
3) 3D co-alignment of the intermediate 25m/pixel HRSC DTM mosaic from step (2) and the intermediate 50m/pixel MOLA-co-aligned HRSC DTM mosaic from step (1), to produce the 25m/pixel MOLA-co-aligned HRSC DTM mosaic, which is the first of the three final products of this work.
4) CASP-GO photogrammetric DTM production of CTX serendipitous "stereo" images to produce 18m/pixel CTX DTMs, which are co-aligned with the 25m/pixel MOLA-co-aligned HRSC DTM mosaic from step (3), as well as 6m/pixel CTX ORIs, which are co-registered with the input 12.5m/pixel HRSC MC-11W level 5 ORI mosaic.

5) MADNet DTM production using the intermediate 6m/pixel HRSC-co-registered CTX ORIs from step (4) to produce intermediate 12m/pixel CTX DTMs.
6) 3D co-alignment of the intermediate 12m/pixel CTX DTMs from step (5) and the 18m/pixel HRSC-co-aligned CTX DTMs from step (4) to produce 12m/pixel HRSC-co-aligned CTX DTMs.
7) DTM mosaicing (using the NASA Ames Stereo Pipeline "dem_mosaic" function) of the 12m/pixel HRSC-co-aligned CTX DTMs from step (6) to produce a 12m/pixel HRSC-co-aligned CTX DTM mosaic, which is the second of the three final products of this work.
8) Image co-registration (using the mutual shape adapted scale invariant features) of the input 25-50cm/pixel HiRISE images with respect to the 6m/pixel HRSC-co-registered CTX ORIs from step (4).
9) MADNet DTM production using the CTX-co-registered HiRISE images from step (8) to produce intermediate 50cm/pixel HiRISE DTMs.
10) 3D co-alignment of the intermediate 50cm/pixel HiRISE DTMs from step (9) and the 12m/pixel HRSC-co-aligned CTX DTM mosaic from step (7) to produce CTX-co-aligned 50cm/pixel HiRISE DTMs.
11) DTM mosaicing of the 50cm/pixel CTX-co-aligned HiRISE DTMs from step (10) to produce a 50cm/pixel CTX-co-aligned HiRISE DTM mosaic, which is the third of the three final products of this work.

4. ARCHIVE FORMAT AND CONTENT

4.1 Product Type

The final outputs of the mapping work include a 25m/pixel HRSC DTM mosaic covering about a 197km×182km area of the landing site (see Figure 5), a 12m/pixel CTX DTM mosaic covering about a 114km×117km area of the landing site (see Figure 6), and a 50cm/pixel HiRISE DTM mosaic (see Figure 7) covering about a 74.3km×86.3km area of the 3-sigma landing ellipses and partially the ExoMars team's geological characterisation area. It should be noted that all final outputs are 3D co-aligned with the reference MOLA DTM using the B-spline fitting based 3D co-alignment method. The complete set of Oxia Planum DTM mosaic products for each of the HRSC, CTX, and HiRISE instruments contains the following types of products:

- DTM mosaic (Mars areoid)
- single-strip ORIs

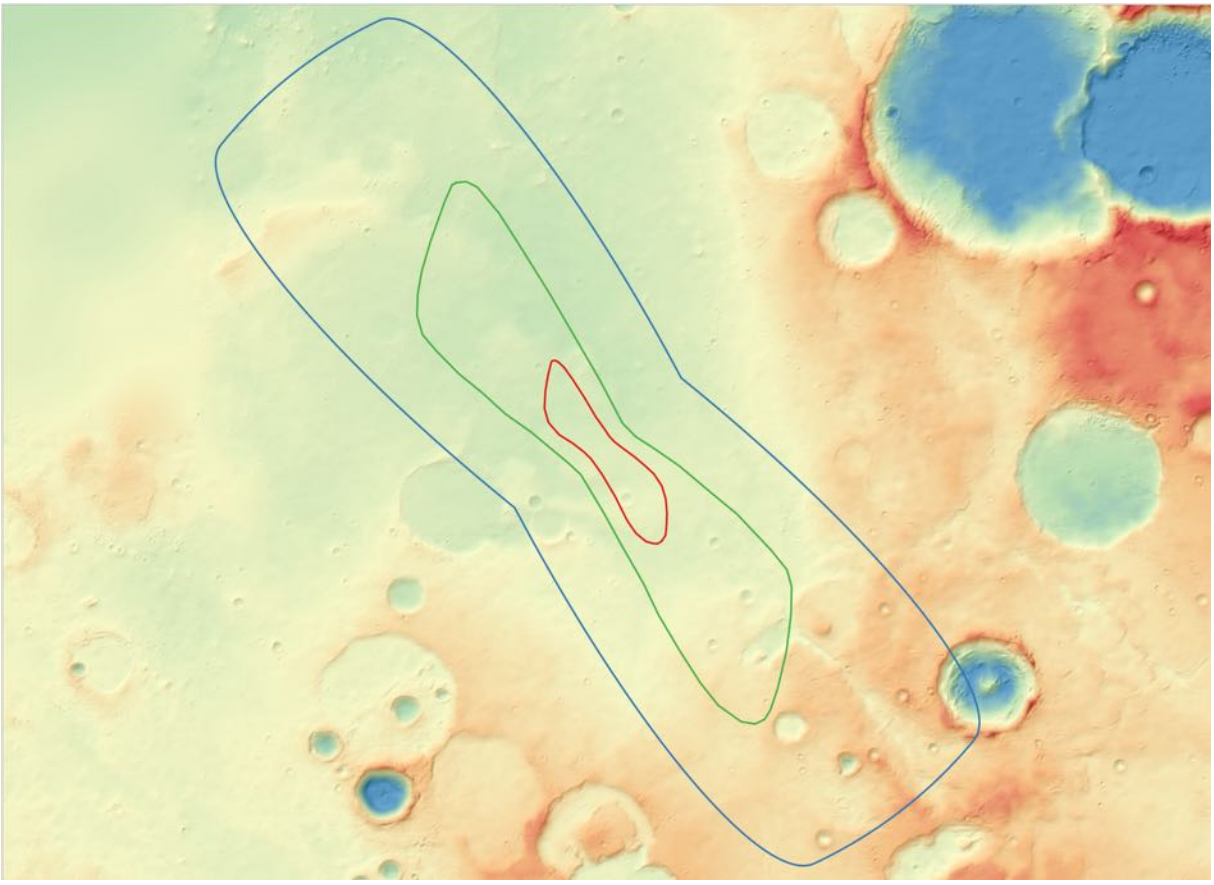

Figure 5. Coverage of the MADNet 1.0 HRSC 25m DTM showing showing the 1-sigma (in red) and 3-sigma (in green) landing ellipse as of the date of this document and the geological mapping area (in blue).

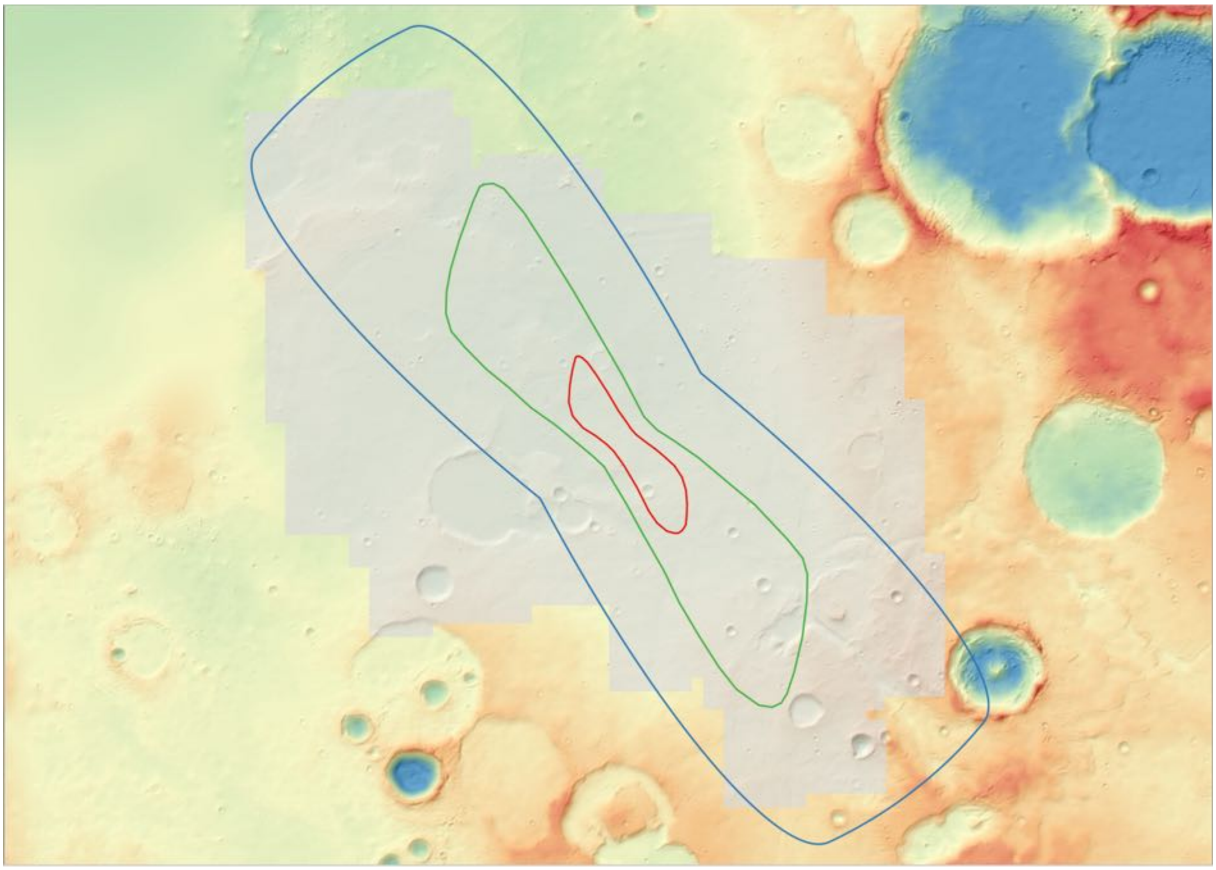

Figure 6. Colourised and hill-shaded CTX MADNet 12m DTM superimposed on top of HRSC MADNet 1.0 25m DTM showing the 1-sigma (in red) and 3-sigma (in green) landing ellipse as of the date of this document and the geological mapping area (in blue).

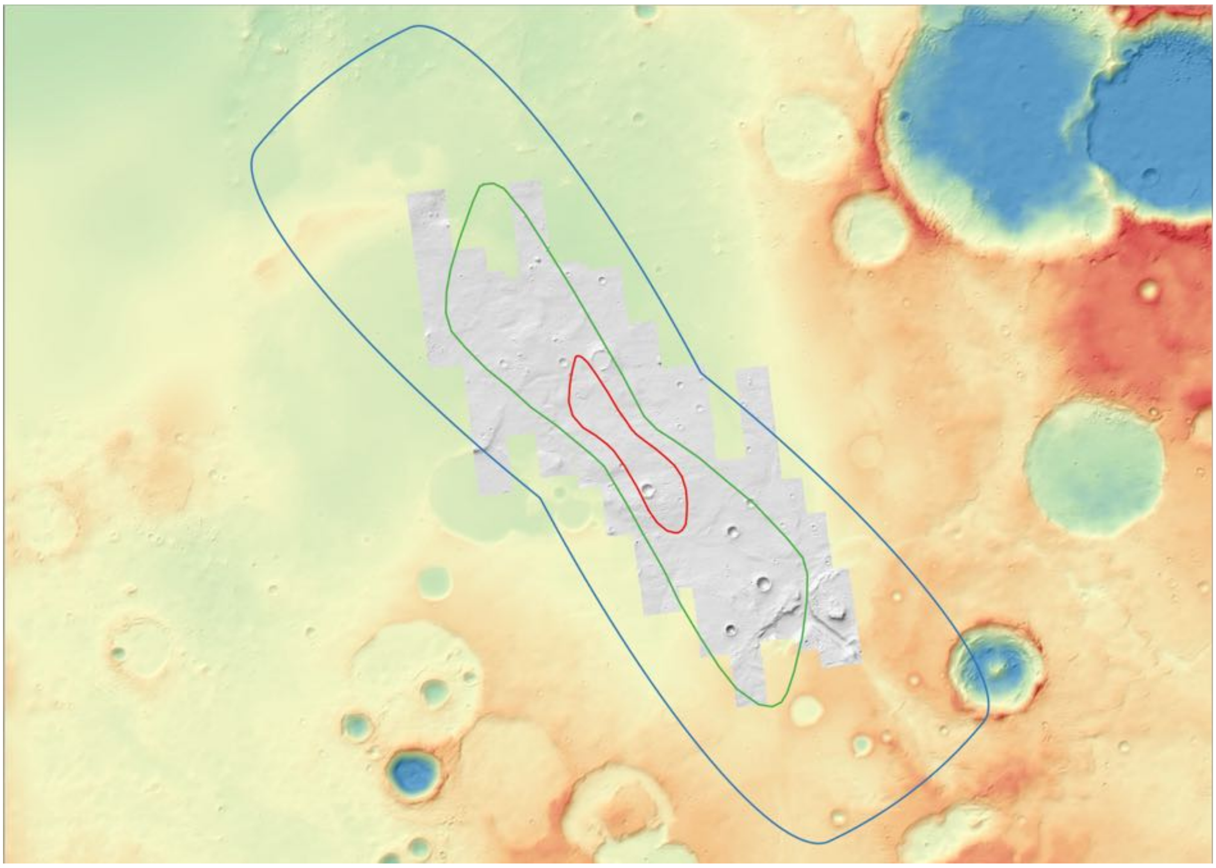

Figure 7. HiRISE MADNet 1.0 0.5m DTM superimposed on MADNet 1.0 CTX 12m DTM superimposed on MADNet 1.0 HRSC 25m DTM all using the same colour hill-shaded parameters with reduced colour for the HiRISE showing the 1-sigma (in red) and 3-sigma (in green) landing ellipse as of the date of this document and the geological mapping area (in blue).

Filename (see further details below the table)	Grid m	NS	NL	Size (Gb)	Top-left lon,lat extent	Bottom-right lon,lat
MOLA_463m_OXIA_CROP_HRSC-Proj.tif (1)	463	663	519	-	26.030W 19.772N	22.706W 16.706N
HRSC-OxiaPlanum-MADNet-DTM.tif (2)	25	7880	7270	0.131	26.030W 19.772N	22.706W 16.706N
HMC_11W24_ND5_OXIA_CROP.tif (3)	12.5	15991	14711	0.235	- “ -	- “ -
CTX-OxiaPlanum-MADNet-DTM.tif (4)	12	9501	9771	0.128	25.366W 19.116N	23.443W 17.138N
CTX-ORIs/*.tif (∑=6) (5)	6	-	-	2.1	- “ -	- “ -
HiRISE-OxiaPlanum-MADNet-DTM-mosaic44.tif (6)	0.5	148697	172508	18	24.922W, 18.865N	23.668W 17.409N
HiRISE-ORIs/*.tif (∑=44) (7)	0.25	-	-	76.9	- “ -	- “ -

N.B.

1. The 463m/pixel PDS MOLA global areoid DTM, cropped for the Oxia Planum area and reprojected using the same projection system as the 12.5m/pixel ESA/DLR/FU-Berlin HRSC MC-11W products
2. The 25m/pixel MADNet HRSC DTM mosaic co-aligned with MOLA
3. The 12.5m/pixel ESA/DLR/FU-Berlin HRSC MC-11W level 5 ORI mosaic cropped for the Oxia Planum area
4. The 12m/pixel MADNet CTX DTM mosaic co-aligned with the 25m/pixel MADNet HRSC DTM mosaic over Oxia Planum
5. The 6m/pixel UCL CTX single-strip ORIs co-registered with the 25m/pixel MADNet HRSC DTM mosaic over Oxia Planum
6. The 50cm/pixel MADNet HiRISE DTM mosaic co-aligned with the 12m/pixel MADNet CTX DTM mosaic over Oxia Planum
7. The 25cm/pixel HiRISE single-strip images, map-projected to MOLA and co-registered with the 6m/pixel UCL CTX single-strip ORIs over Oxia Planum.

4.2 DTM/ORI Specification

- Projection: Equirectangular [1]
- Mars radius reference: MOLA aeroid (da) [2]

4.3 Product Example and Usage

The DTM and ORI file in GeoTiff format can be opened in GIS/image processing software such as ArcGIS, QGIS, and ENVI. Projection and mapping information is embedded in the header of the Geotiff file.

The best way to visually inspect a DTM is via a colourised hill-shaded display. The following instructions show how to create a colourised hill-shaded view of the DTM product in QGIS.

[1] https://en.wikipedia.org/wiki/Equirectangular_projection

[2] https://astrogeology.usgs.gov/search/map/Mars/GlobalSurveyor/MOLA/Mars_MGS_MOLA_DEM_mosaic_global_463m

1. Import the DTM via: Layer -> Add layer -> Add Raster Layer -> Select the Raster dataset(s) -> Add -> Close
2. Create shaded relief image: left click to select the DTM -> Raster -> Analysis -> Hillshade -> Select the illumination parameters (e.g., z=2, azimuth=330, elevation=30) under "Hillshade" click "..." -> save to file -> choose a filename and end with .tif -> OK -> run -> close
3. Adjust the display setting of the shaded relief image: right click the hill-shaded relief image -> Properties -> Symbology -> under "Color Rendering" select "Blending mode" -> "Overlay" -> adjust "Brightness" as "-60" -> Apply -> OK.
4. Adjust the display setting of the DTM: right click the DTM -> Properties -> Symbology -> under "Band Rendering" select "Render type" as "Singleband pseudocolor" -> under "Min/Max Value Settings" select Min/Max -> under "Color ramp" select a colour ramp then select "Invert Color Ramp" -> click "Classify" -> Apply -> OK

Other important notes:

1. Put the hillshaded relief image layer in front of the colourised DTM layer.
2. Do not use transparency for the hillshaded relief image layer as "Overlay" display mode is already selected.
3. You can use z=3 if a strong hill-shading effect is needed.
4. Always create a group for the colourised DTM and hillshaded relief image, and use the group icon to toggle display of the colourised hillshaded DTM.

5. KNOWN ISSUES

The resultant 50cm/pixel HiRISE MADNet DTM mosaic has some known artefacts. These include the tiling artefacts, smoothing issues, DTM gaps due to insufficient overlap of HiRISE images, and linear artefacts due to missing data within the HiRISE image (only found in strips). Figure 8 provides an example for each of the four known artefacts within the hill-shaded images and show how much they would affect the DTMs. The affected areas are considered minor (less than 0.2% of the total number of pixels) within the mosaic. It should also be noted that the HRSC and CTX MADNet DTM mosaics do not have any of these artefacts.

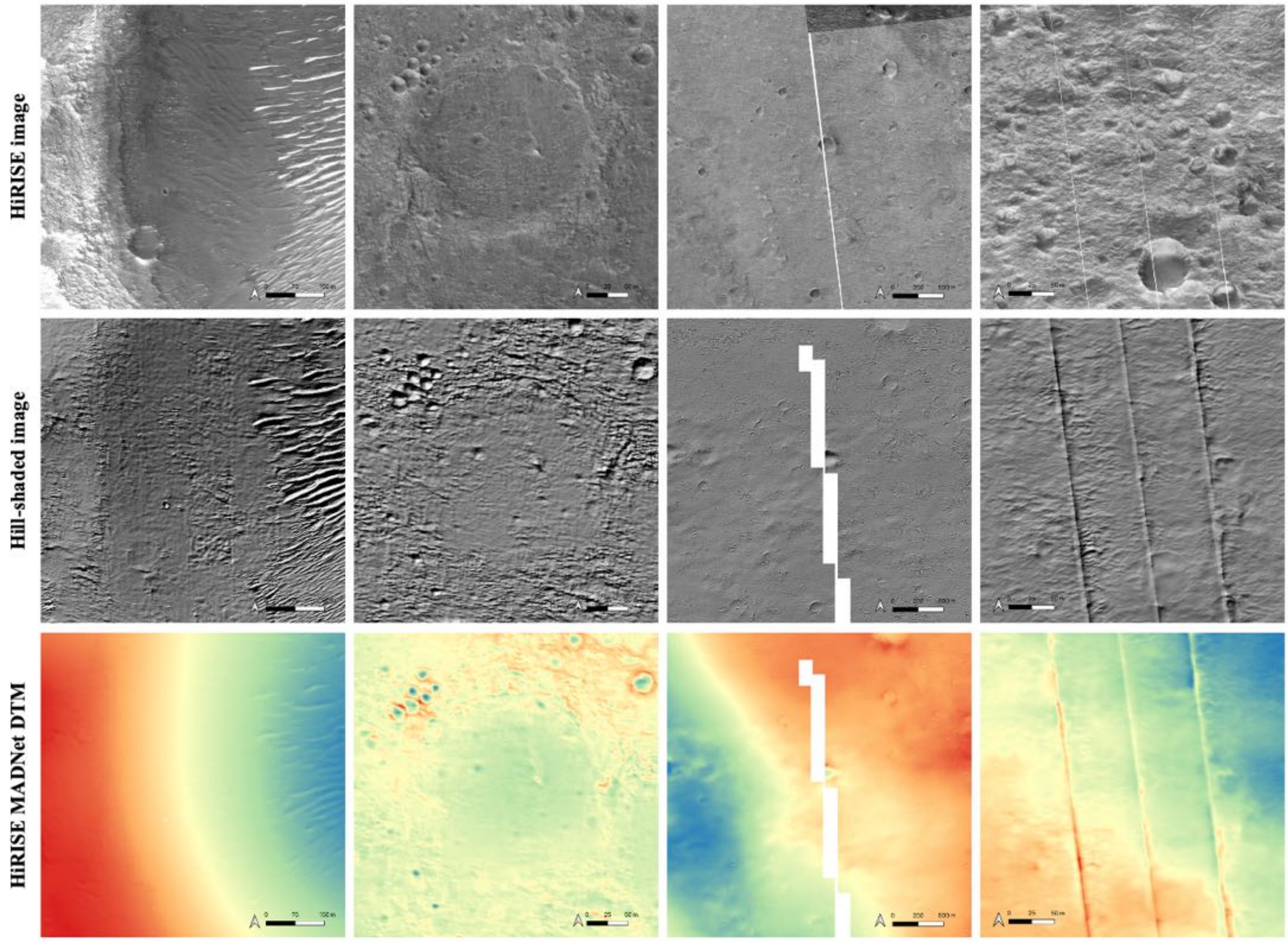

Figure 8. Examples of known artefacts of the HiRISE MADNet DTM mosaic, i.e., 1st column: tiling artefacts; 2nd column: smoothing issues; 3rd column: missing columns in the original HiRISE image; 4th column: linear artefacts due to the use of JPEG2000 HiRISE images that do not have the correct radiometric de-calibration. Hill-shaded image is created using the HiRISE MADNet DTM mosaic with illumination azimuth 330°, elevation 30°, and a vertical exaggeration factor of three times.

6. SOFTWARE

The processing uses the UCL's in-house MADNet 1.0 single-image DTM estimation system.