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SPAIN

CTX DIGITAL TERRAIN MODEL AND TERRAIN-CORRECTED IMAGES OF MARS

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APPROVAL

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Issue 1	**Revision** 0		
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Table of contents:

1. INTRODUCTION

Within the EU FP-7 iMars project (http://www.i-mars.eu), UCL developed a fully automated multi-resolution DTM processing chain for NASA MRO CTX and HiRISE stereo processing, called the CASP-GO (***Tao et al., PSS, 2018***), based on the open source NASA ASP (***Beyer et al., ESS, 2018***). CASP-GO employs tie-point based multi-resolution image co-registration (***Tao & Muller, Icarus, 2016***), and Gotcha sub-pixel refinement and densification (***Shin and Muller, PR, 2012***).

The CASP-GO pipeline is used to produce planet-wide CTX and HiRISE DTMs that guarantee global geo-referencing compliance with respect to HRSC, and thence to the MOLA global height reference system, providing refined stereo matching completeness and accuracy. The CASP-GO software and products with the highest quality levels are being made open-source to the planetary science community through NASA Ames Github software (in 2021/2) and the products through the ESAC GSF (2020). The browse products are accessible through the iMars WebGIS system (http://www.i-mars.eu/webgis) which is described in ***Walter et al. (2018).***

1.1 Instrument and datasets

The MRO CTX instrument captures repeat pass single panchromatic grey-scale images at ~6m/pixel over a swath-width of 30km with a large number with suitable stereo angles. A total of ~5,300 planet-wide CTX stereo pairs were processed by UCL using the CASP-GO system ported to the Microsoft® Azure® computing cloud. Within the ~5,300 input stereo pairs, ~3,800 CTX product browse images for the DTMs have been visually inspected and classified into 5 quality levels. The top two quality products are the ones released to the scientific community.

1.2 Abbreviations and Acronyms

ALSC	Adaptive Least Square Correlation
ASP	Ames Stereo Pipeline
CASP-GO	Co-registration ASP Gotcha Optimised
CTX	Context Camera
DTM	Digital Terrain Model
EU FP-7	European Union's Seventh Framework Programme
ESA	European Space Agency
ESAC	European Space Astronomy Centre
GIS	Geographic Information System
GSF	Guest Storage Facility (ESA-ESAC-PSA)
HiRISE	High Resolution Imaging Science Experiment
HRSC	High Resolution Stereo Colour imaging
ISIS	Integrated Software for Imagers and Spectrometers
PSA	Planetary Science Archive
PVL	Parameter Value Language (used by ISGS)
MOLA	Mars Orbiter Laser Altimeter
MRO	Mars Reconnaissance Orbiter
ORI	OrthoRectified Images
PUG	Product User Guide
UCL	University College London
webGIS	web based Geographic Information System

1.3 Reference and Applicable Documents

Beyer, Ross A., Oleg Alexandrov, and Scott McMichael. 2018. The Ames Stereo Pipeline: NASA's open source software for deriving and processing terrain data. Earth and Space Science, 5. DOI: 10.1029/2018EA000409.

Tao, Y., Muller, J.P., Sidiropoulos, P., Xiong, S.T., Putri, A.R.D., Walter, S.H.G., Veitch-Michaelis, J. and Yershov, V., 2018. Massive stereo-based DTM production for Mars on cloud computers. Planetary and Space Science, vol. 154, pp.30-58. DOI: 10.1016/j.pss.2018.02.012

Tao, Y., Muller, J.P. and Poole, W.D., 2016. Automated localisation of Mars rovers using co-registered HiRISE-CTX-HRSC orthorectified images and wide baseline Navcam orthorectified mosaics. Icarus, vol. 280, pp. 139-157. DOI: 10.1016/j.icarus.2016.06.017

Shin, D. and Muller, J.P., 2012. Progressively Weighted Affine Adaptive Correlation Matching for Quasi-Dense 3D Reconstruction. Pattern Recognition, 45(10), pp.3795-3809. DOI: 10.1016/j.patcog.2012.03.023

Smith, D.E., Sjogren, W.L., Tyler, G.L., Balmino, G., Lemoine, F.G., and Konopliv,A.S., 1999. The gravity field of Mars—Results from Mars Global Surveyor. Science, 286, p. 94–97. DOI: 10.1126/science.286.5437.94

Walter, S. H. G.; Muller, J. P.; Sidiropoulos, P.; Tao, Y.; Gwinner, K.; Putri, A. R. D.; Kim, J. R.; Steikert, R.; vanGasselt, S.; Michael, G. G.; Watson, G.; Schreiner, B. P., 2018. The Web-based Interactive Mars Analysis and Research System for the iMars project. *Earth and Space Science,* 5, 308-323, DOI: 10.1029/2018EA000389

2. SCIENTIFIC OBJECTIVES

During the past 5 decades, many areas on Mars have been imaged with serendipitous stereo, mainly to improve the potential for scientific studies. The rapid progress in planetary surface reconnaissance instrumentation, especially in relation to 3D imaging of the surface, has allowed change detection analysis. For example, by overlaying different high-resolution imagery from distinct time epochs (starting back to the mid 1970's) one can examine dynamic features, such as the recent discovery on Mars of mass (e.g. boulder) movement, tracking inter-year changes of seasonal phenomena (e.g. Swiss Cheese Terrain) and looking for fresh craters from meteoritic impacts.

It is common knowledge in the planetary scientific community that research greatly benefits from the availability of high-resolution 3D models of Mars. Within the EU FP-7 iMars (http://www.i-mars.eu) project, we focused on developing tools and producing value-added datasets to maximize the exploitation of the available planetary datasets of the Martian surface. This includes the generation of high quality co-registered DTMs and corresponding terrain-corrected ORIs, using data from different NASA and ESA instruments.

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 (10.5270/esa-tk7pcfp) and the paper describing the processing system, assessment, and final product generation:

Tao, Y., Muller, J.P., Sidiropoulos, P., Xiong, S.T., Putri, A.R.D., Walter, S.H.G., Veitch-Michaelis, J. and Yershov, V., 2018. Massive stereo-based DTM production for Mars on cloud computers. *Planetary and Space Science, **154**, pp.30-58.* DOI: 10.1016/j.pss.2018.02.012

Accessible at: https://www.cosmos.esa.int/web/psa/UCL-MSSL_iMars_CTX_v1.0

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under iMars grant agreement n° 607379 as well as partial funding from the STFC "MSSL Consolidated Grant" ST/K000977/1 and from the UK Space Agency Aurora support under project no. ST/S001891.

3. DATA PRODUCT GENERATION

The CASP-GO pipeline is based on the NASA Ames Stereo Pipeline (ASP) with enhancements from in house software developed previously. CASP-GO takes ISIS formatted "left" and "right" MRO CTX images and a reference HRSC ORI as inputs. It uses a combination of the ASP functions and the 5th generation of an adaptive least squares correlation and region growing matcher called Gotcha (Shin & Muller, 2012), which provides accurate and robust sub-pixel conjugate points. CASP-GO generates raster products such as ORIs and DTMs that are co-registered to HRSC.
The complete CASP-GO workflow for CTX DTM production has the following 9 steps: (1) ASP "left" and "right" image pre-processing (image normalisation, Laplacian of Gaussian filtering, pre-alignment); (2) ASP disparity map initialisation (pyramid cross-correlation to build a rough disparity map); (3) UCL fast Maximum Likelihood matching and building of a "float" initial disparity map; (4) ASP Bayes Expectation Maximisation weighted affine adaptive sub-pixel cross-correlation; (5) UCL refined outlier rejection gap erosion scheme to remove and eliminate mis-matched and unreliable disparity values; (6) UCL ALSC based sub-pixel refinement; (7) UCL Gotcha (ALSC with region growing) based refinement and densification method to refine the disparity value and match un-matched or mis-matched area; (8) UCL co-kriging grid-point interpolation to generate ORI and DTM as well as height uncertainties for each DTM point; (9) UCL ORI co-registration/geocoding with reference to HRSC orthoimage and DTM adjustment. Each of these function extensions/modifications (labelled as the UCL pipeline) have been discussed in more detail in (***Tao et al., PSS, 2018***).

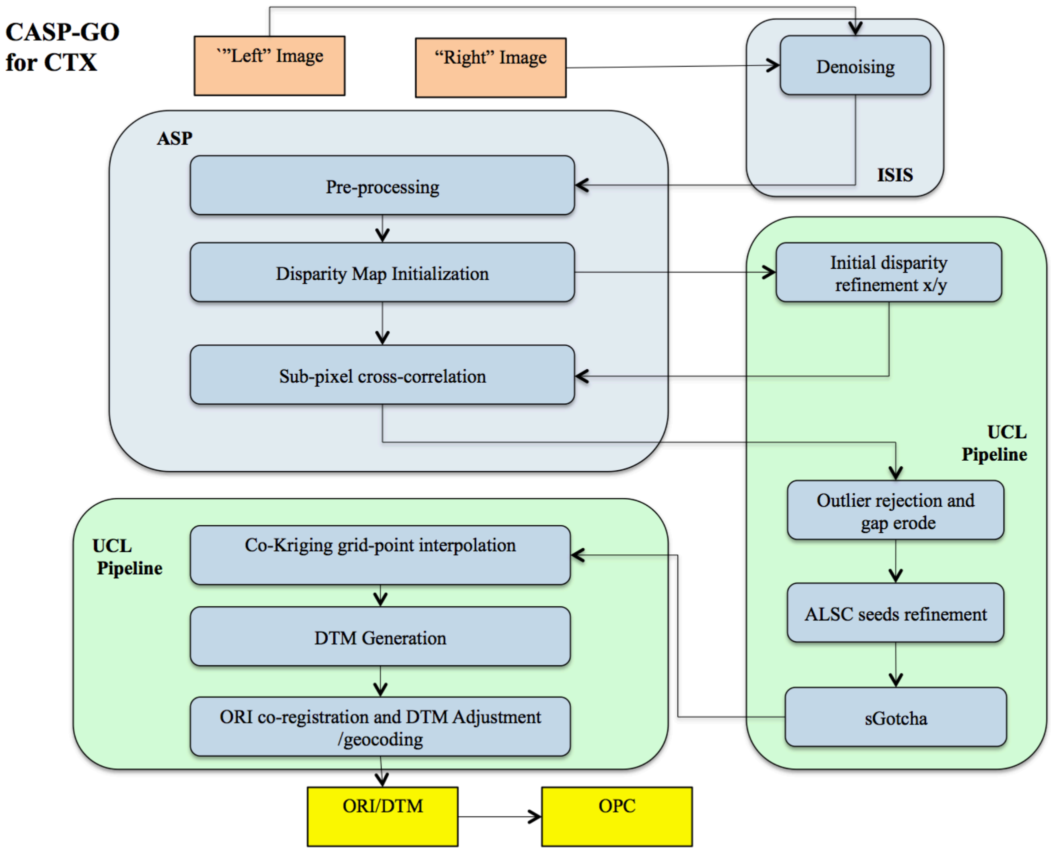


Figure 1 Flow diagram of the UCL-ASP "CASP-GO" processing chain for CTX DTM processing.

4. ARCHIVE FORMAT AND CONTENT

4.1 Product type

A complete set of iMars 3D product for one pair of stereo CTX images contains the following types of products:

- DTM (Mars areoid)
- ORI
- Metadata file

The following are also produced but are not included in this first release

- Uncertainty map
- Point cloud file
- Gotcha mask
- Co-kriging interpolation mask
- Hill-shaded colourised browser products

4.2 Naming convention

When each product is processed the following set of files is contained in a directory with a naming convention of LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID. The naming convention for the different types of products listed above is as follows:

- DTM (areoid): LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-DTM_UCL.tif
- ORI: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-ORI_UCL.tif
- Metadata file: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-Meta.txt

The following additional product layers are not distributed at present:

- Uncertainty map: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-F.tif
- Point cloud file: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-PC.tif
- Gotcha mask: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-GM.tif
- Co-kriging mask: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-CM.tif
- Uncertainty map: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-uncertainty.tif
- browser products: LEFT_CTX_IMAGE_ID-RIGHT_CTX_IMAGE_ID-browse.tif

The CTX file-naming convention is explained at https://github.com/USGS-Astrogeology/ISIS3/wiki/Working_with_Mars_Reconnaissance_Orbiter_CTX_Data#File-Naming-Convention-

4.3 Format type

- DTM: float32; 1 channel; Geotiff image.
- ORI: float32; 1 channel; Geotiff image.
- Metadata file: ASCII file in PVL format

The following additional product layers are not distributed at present:

- Disparity map: float32; 3 channels; Tiff image.
- Point cloud file: float32; 4channels; Tiff image.
- Gotcha mask: uint8; 1 channel; Tiff image.
- Co-kriging interpolation mask: uint8; 1 channel; Tiff image
- Uncertainty map: float32; 1 channel; Geotiff image
- Hill-shaded colourised browser products: uinit8; 3 channels; JPG image

4.4 DTM/ORI specification

- Projection: Equirectangular
- Mars radius reference: MOLA aeroid
- DTM resolution: 18m/pixel
- ORI resolution: 6m/pixel
- NoData value: -3.4028234663852886e+38

4.5 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. In the PVL file, producer, data information and processing parameters are available.

Example of GeoTIFF header of B09_013308_1810_XI_01N010W-B10_013664_1810_XI_01N010W-DTM.tif

```
Driver: GTiff/GeoTIFF
Files: B09_013308_1810_XI_01N010W-B10_013664_1810_XI_01N010W-DTM.tif
Size is 2106, 5814
Coordinate System is:
PROJCS["unnamed",
    GEOGCS["Geographic Coordinate System",
        DATUM["unknown",
            SPHEROID["Unknown",3396000,0]],
        PRIMEM["Greenwich",0],
        UNIT["degree",0.0174532925199433]],
    PROJECTION["Equirectangular"],
    PARAMETER["latitude_of_origin",0],
    PARAMETER["central_meridian",0],
    PARAMETER["standard_parallel_1",0],
    PARAMETER["false_easting",0],
    PARAMETER["false_northing",0],
    UNIT["metre",1,
        AUTHORITY["EPSG","9001"]]]
Origin = (-647351.228660562424920,113899.064877414435614)
Pixel Size = (18.000000000000000,-18.000000000000000)
Metadata:
  AREA_OR_POINT=Area
Image Structure Metadata:
  INTERLEAVE=BAND
Corner Coordinates:
Upper Left  ( -647351.229,  113899.065) ( 10d55'18.54"W,  1d55'17.95"N)
Lower Left  ( -647351.229,    9247.065) ( 10d55'18.54"W,  0d 9'21.64"N)
Upper Right ( -609443.229,  113899.065) ( 10d16'56.10"W,  1d55'17.95"N)
Lower Right ( -609443.229,    9247.065) ( 10d16'56.10"W,  0d 9'21.64"N)
Center      ( -628397.229,   61573.065) ( 10d36' 7.32"W,  1d 2'19.80"N)
Band 1 Block=256x256 Type=Float32, ColorInterp=Gray
  NoData Value=-3.4028234663852886e+38
```

Example of B09_013308_1810_XI_01N010W-B10_013664_1810_XI_01N010W-Meta.txt

```
Object = AutoDTM
  Object = ProductInfo
    Object = Processing
      SoftwareName = CASP-GO
      SoftwareVersion = 1.0
      OperatingSystem = "RHEL v6"
```

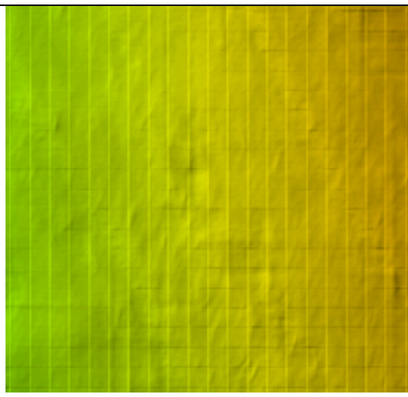
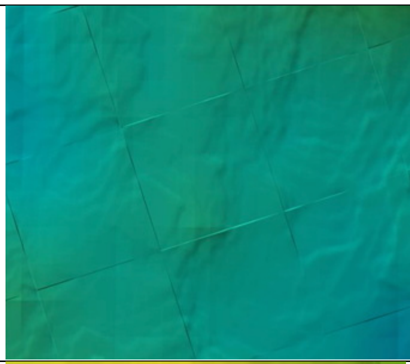
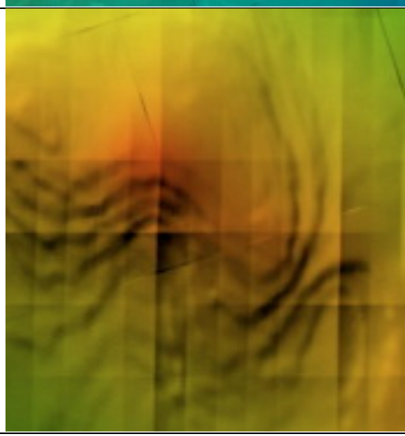
```
    ProcessingStartTime = 2015-12-22T18:17
    ProcessingEndTime = 2016-05-31T15:37
    ProcessingOrganisation = UCL/MSSL
    ProcessingResource = "Imaging Group Blades"
    ContactPerson = "Yu Tao"
    ContactEmail = "yu.tao{at}ucl.ac.uk"
  End_Object
  Object = Data
    ID = B09_013308_1810_XI_01N010W-B10_013664_1810_XI_01N010W
    Format = GeoTiff
    Band = 1
    BitDepth = 32f
    DTMResolution = 18
    ORIResolution = 6
    Unit = Metre
    NodataValue = -3.4028234663852886e+38
    Projection = Equirectangular
  End_Object
End_Object
Object = Algorithm
  Group = ASP
    Name = "Ames Stereo Pipeline Function Parameters"
    InitialCorrKernel = 75
    RefinementCorrKernel = 105
    RefinementIteration = 3
  End_Group
  Group = sGotcha
    Name = "Adaptive Least Squares Correlation and Region growing Parameters"
    ALSCIteration = 8
    MaxEigenValue = 150
    ALSCKernel = 21
    GrowNeighbour = 8
  End_Group
  Group = ML
    Name = "Fast Maximum Likelihood Matching Parameters"
    MLKernel = 25
    MLIter = 3
  End_Group
  Group = ORS
    Name = "Outlier Rejection Schemes Parameters"
    MaxDiff = 1.5
    PercentDiff = 60
    DiffKernel = 21
    PatchThreshold = 7.5
    PercentReject = 25
    Erode = 1
  End_Group
  Group = coKriging
    Name = "Co-Kriging Interpolation Parameters"
    NeighbourLimit = 21
    DistLimit = 500
    SpatialResRatio = 1
  End_Group
  Group = MSA-SIFT
    Name = "Mutual Shape Adapted Scale Invariant Feature Transform Co-registion Parameters"
    nOctave = 8
    EdgeThreshold = 10
    MatchCoeff = 0.6
    nLayer = 3
  End_Group
```

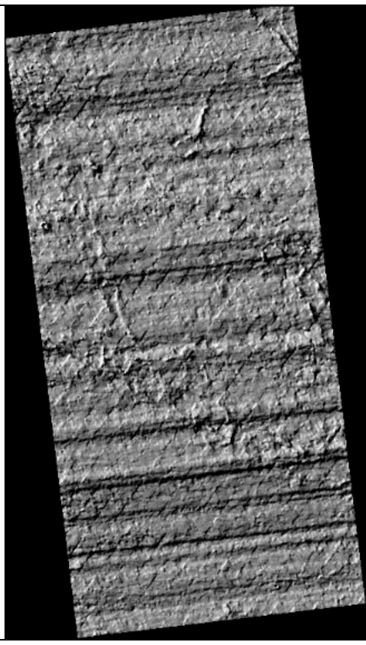
```
  End_Object
End_Object
End
```

5. KNOWN ISSUES

There are known artefacts present in the CTX DTMs released. Efforts have been made to try to reduce these artefacts, but looking at the individual colourised_by_height hillshaded relief maps to check whether the Region of Interest is affected is suggested before using the DTM for any quantitative purposes. These artefacts have been exaggerated as most are <1-2m in height. There are similar artefacts in HRSC and HiRISE products.

Table 1. Known Issues in DTM Products

Issue	Explanation	Illustration
Square artefact	The square artefact is caused by converting the DTMs from spherical reference (DT) to DA reference (areoid) using a MOLA DT-DA difference map (the dem_geoid function in ASP). The size of each square's edge is exactly the same as the MOLA pixel size (463m/pixel). Reducing the effect of this artefact is possible by using an upscaled MOLA DTM, however, this takes a long time to compute and requires a large amount of disk space.	
Tiling artefact	The tiling artefact is produced sometimes as a result of matching the stereo images with smaller tiles that have insufficient overlapping area or bad agreement of the matching results of different tiles.	
Contouring	Contouring artefact is produced when the matching window is not small enough over steep slopes.	

Jitter artefact	Currently there is no jitter detection and automated correction method for CTX images. Dejittering is possible manually via USGS ISIS suites. We have developed an automated dejittering system for HRSC and this has been applied successfully to CTX. This is the subject of a paper in preparation (Tao, Muller et al.).	

6. SOFTWARE

CASP-GO will be released in 2021/2 via NASA Ames Github as part of a NASA project
https://github.com/NeoGeographyToolkit