



Erasmus Plus GeoPlaNet Strategic Partnership

IO6: Digital Elevation Model generation

FINAL REPORT

1. Summary

This tutorial has been prepared by the University d'Annunzio in collaboration with the University of Padova and the whole consortium of the Erasmus+ Strategic Partnership GeoPlaNet-SP (ref. 2020-1-FR01-KA203-079773). The context is the summer school on Planetary Geological Mapping and Field Analogues organized in the framework of the same partnership.

The aim is to describe the pipeline developed to generate Digital Elevation Models (DEMs) from planetary data. We select Mars as the target because of the amount of available datasets and the variety of geological landforms present on the planet. As the exemplary tool material, we select Context Camera (CTX) images, because this is a dataset that was not originally conceived for the 3D analysis purpose, hence it allows us to understand how to face potential issues. As the test area, we selected the Eberswalde crater, centered at 23.9W-33.25S, and in particular the central part of the crater, where the famous delta feature (Malin and Edgett, 2002; Bhattacharya et al., 2005; Pondrelli et al., 2008; Mangold et al., 2012) propagates into the basin floor. Here, the variety of morphologies and geometries of the landforms represent an ideal test area both for technical issues and scientific purposes. The overall procedure includes data selection, pre-processing, and finally DEM generation.

2. Data selection

Most of the planetary data, and all of the data coming from NASA and ESA, are archived in the Geosciences Node of NASA's Planetary Data System (PDS):

1. <https://pds-geosciences.wustl.edu>

Data can be searched in different ways (e.g., coordinates, product IDs, time range, map search...) (Fig. 1). Image footprints can also be downloaded for a more straightforward evaluation of data distribution. Moreover, within the data footprints associated metadata, the download link is included, thus allowing to automatize data selection and save time in the project preparation.

During the process of data selection, potential stereo pairs can also be identified. Still, the presence of overlapping images does not necessarily imply that the images can eventually produce a DEM. This is especially true for the datasets which were not acquired with the original purpose to produce DEMs, mostly as a result of a. the convergence angle of the stereo pair that as it increases, the image matching precision decreases approximately linearly, which makes the georegistration less precise and b. the shadow-tip distance and aspect ratio that are also roughly linear with image matching precision.

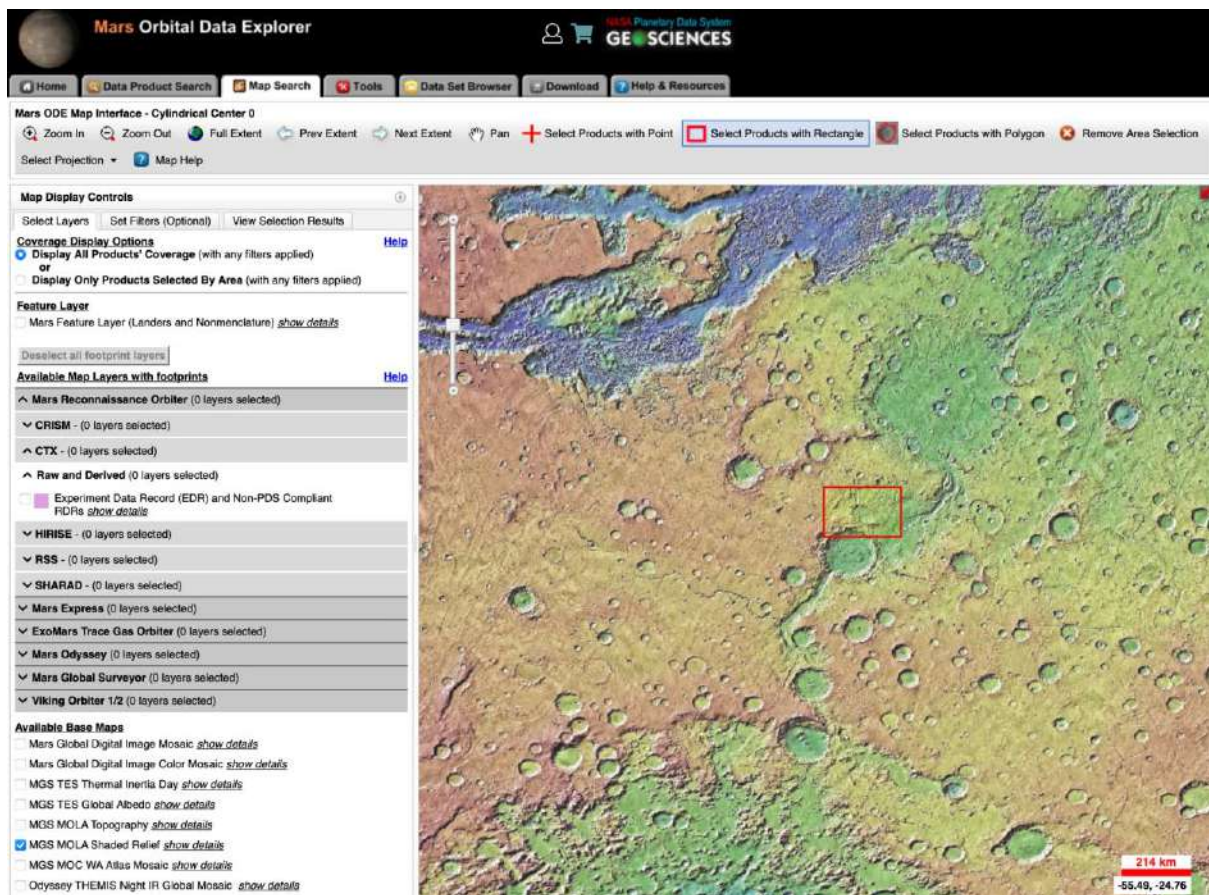


Figure 1 - Screenshot from the PDS Geosciences Node Mars Orbital Data Explorer (ODE) showing the 'map search' option.

In order to address this issue, the USGS Astrogeology Science Center in the framework of the NASA PDS Cartography and Imaging Science Node developed PILOT (Planetary Image Locator Tool):

2. <https://pilot.wr.usgs.gov>

PILOT is an online data portal used to search through raw image archives of the Cartography and Imaging Sciences ("Imaging" or IMG) Node of NASA's Planetary Data System (PDS). A tutorial is available on the homepage (Fig. 2). Once selected the planetary body of interest, the next step will be the selection of the needed instrument (Fig. 3). The selection needs to be further refined using the map interface or the metadata (advanced). The Stereo tab allows searching for stereo pair images for making Digital Elevation Models (DEMs), with the help of a stereo matcher that provides the possibility to constrain the different parameters to shortlist working stereo pairs (Fig. 4). This is particularly useful when using datasets such as CTX (Context Camera; Malin et al., 2007), which were not originally acquired with the aim to develop stereopairs.

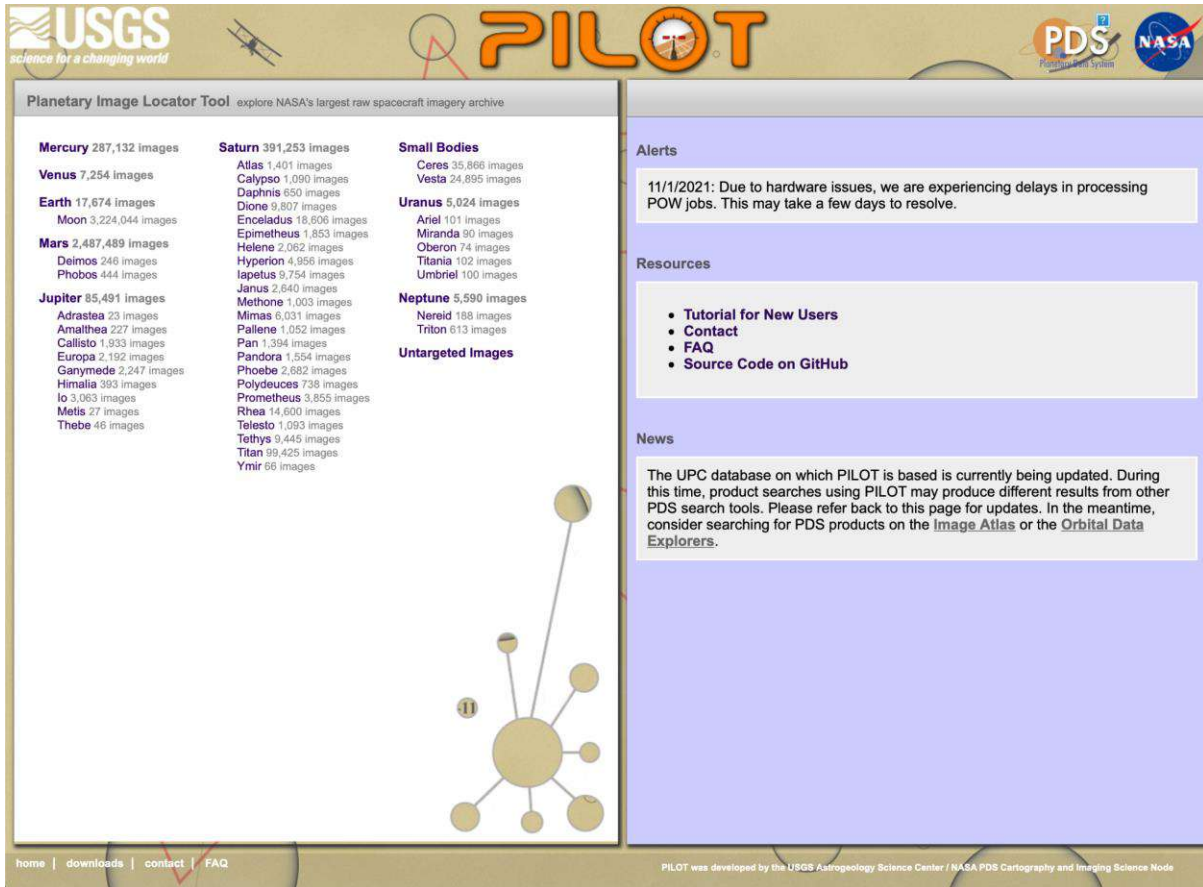


Figure 2 - Screenshot from the Planetary Image Locator Tool (PILOT) home.

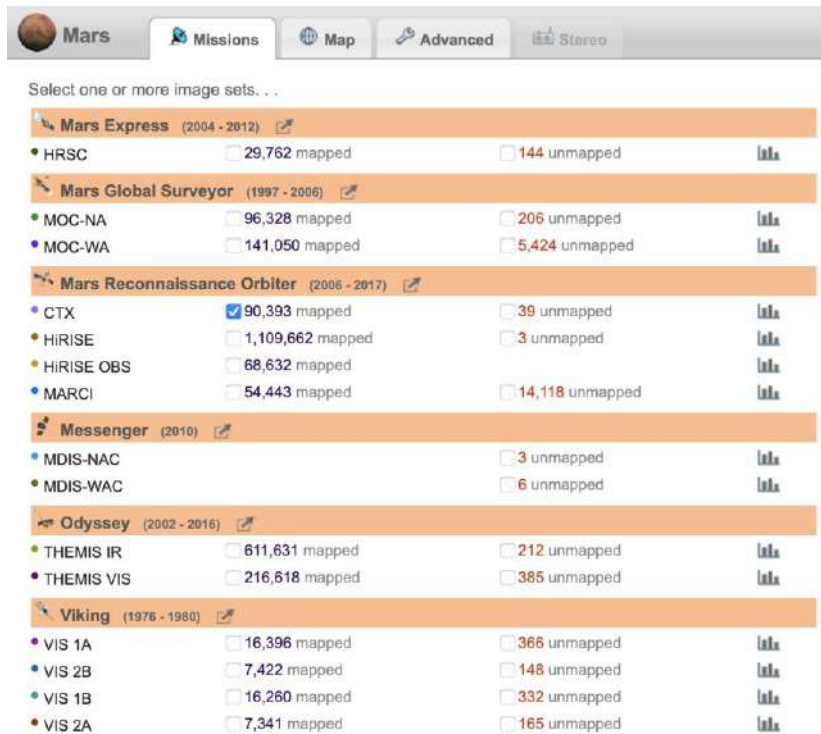


Figure 3 - Screenshot from the Planetary Image Locator Tool (PILOT) interface designed to select the mission. The election can be further refined using the map or the metadata (advanced).

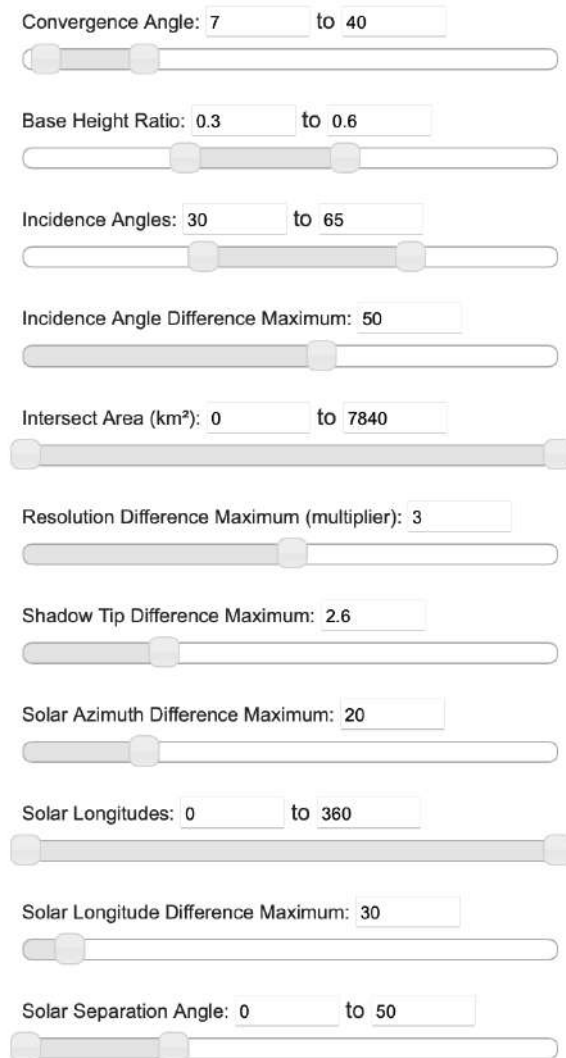


Figure 4 - Screenshot from the PILOT Stereo Matcher

We selected the CTX images:

B02_010474_1558_XI_245033W

(https://ode.rsl.wustl.edu/mars/indexproductpage.aspx?product_id=B02_010474_1558_XI_245033W&product_idGeo=12806129)

B02_010553_1558_XI_245033W

https://ode.rsl.wustl.edu/mars/indexproductpage.aspx?product_id=B02_010553_1558_XI_245033W&product_idGeo=12806312

3. Pre-processing

The NASA Ames Stereo Pipeline (ASP) is the software released to derive DEMs from satellite images:

3. <https://github.com/NeoGeographyToolkit> (Beyer et al., 2018)

The documentation can be found here:

4. <https://stereopipeline.readthedocs.io/en/latest/index.html>

Planetary data is released in a raw format (i.e., original data from an instrument). These data need to be processed, in order to be suitable for scientific investigation. In the framework of the PDS, the US Geological Survey (USGS) released the Integrated Software for Imagers and Spectrometers (ISIS):

5. <https://github.com/USGS-Astrogeology/ISIS3> (Laura et al., 2022)

This software is a requisite for ASP for non-Earth data and can ingest raw data and calibrate them (i.e., convert them to physical units, which makes values independent of the instrument). Although the following commands are specific for CTX images, the logic process is the same for all the planetary imagery datasets.

Both ISIS and ASP work in a UNIX environment. The philosophy and some basic commands are here:

6. <https://swcarpentry.github.io/shell-novice/reference.html>

The pre-processing phase consists in preparing science-ready map-projected images that can be ingested in the stereo algorithm.

The first step consists of the data ingestion within ISIS (conversion in ISIS3 Cube Format https://usgs-astrogeology.github.io/ISIS3/ISIS_Cube_Format.html):

```
mroctx2isis from=B02_010474_1558_XI_245033W.img to=B02_010474_1558_XI_245033W.cub
```

```
mroctx2isis from=B02_010553_1558_XI_245033W.img to=B02_010553_1558_XI_245033W.cub
```

The output can be observed in ISIS using the command 'qview' (Fig. 5).

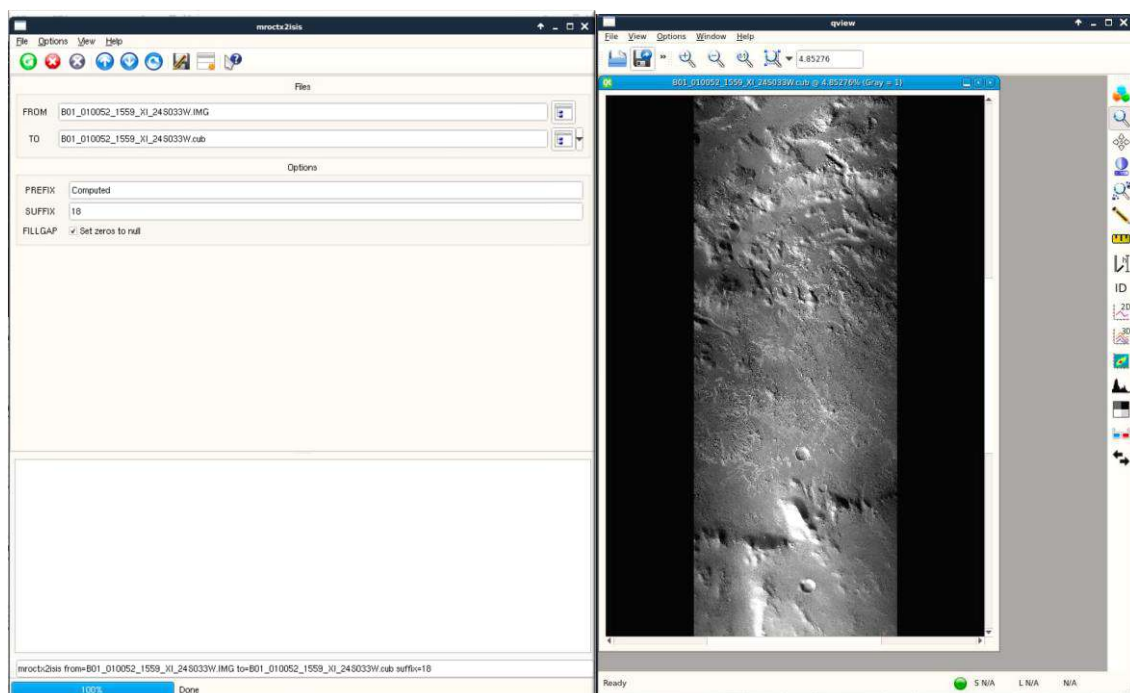


Figure 5 - Screenshots showing the use of the mroctx2isis command (left) and data view.

The second step includes the SPICE kernel ingestion, files containing ancillary data used to determine observation geometry parameters:

```
spiceinit from=B02_010474_1558_XI_245033W.cub
```

```
spiceinit from=B02_010553_1558_XI_245033W.cub
```

The radiometric calibration is necessary because all cameras produce digital images with camera shading. Camera shading is an inherent artifact that results from the non-uniform sensitivity across the field of view of the imaging instrument (Fig. 6):

```
ctxcal from=B02_010474_1558_XI_245033W.cub to=B02_010474_1558_XI_245033W.cal.cub
```

```
ctxcal from=B02_010553_1558_XI_245033W.cub to=B02_010553_1558_XI_245033W.cal.cub
```

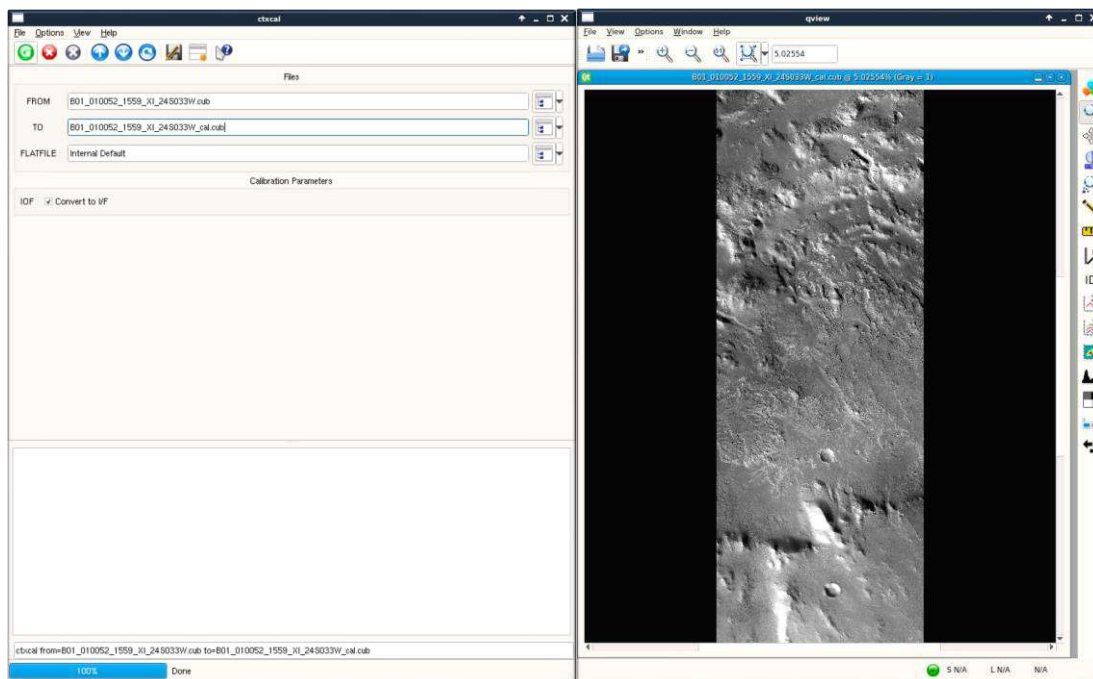


Figure 6 - Screenshots showing the use of the ctxcal command (left) and data view.

The command ctxevenodd, to be strictly used after ctxcal, remove even/odd detector striping from the images:

```
ctxevenodd from=B02_010474_1558_XI_245033W.cal.cub  
to=B02_010474_1558_XI_245033W.eve.cub
```

```
ctxevenodd from=B02_010553_1558_XI_245033W.cal.cub  
to=B02_010553_1558_XI_245033W.eve.cub
```

The program cam2map4stereo.py determines the minimum overlap of the two images, and the worst common resolution, and then map-projects the two images to this identical area and resolution.

```
cam2map4stereo.py B02_010474_1558_XI_245033W.eve.cub  
B02_010553_1558_XI_245033W.eve.cub
```

The results will be two overlapping calibrated and map-projected images:

B02_010474_1558_XI_245033W.map.cub

B02_010553_1558_XI_245033W.map.cub

4. DEM generation

Since severe distortions may arise from satellite position and orientation errors, these problems need to be addressed using the bundle adjustment process. This process takes advantage of the overlapping images to adjust simultaneously their properties and the locations of each pixel. The baseline is that the observation in multiple images must be self-consistent.

```
bundle_adjust B02_010474_1558_XI_245033W.map.cub B02_010553_1558_XI_245033W.map.cub  
-o run_ba/run
```

Where the option `-o` refers to the prefix for output filenames, in the specific case indicated as `run_ba/run` to create a separate folder (here named “run_ba”) for all of the files, including intermediate, produced. The second “run” indicates the prefix to be given to the result files (e.g. `run-PC.tif`, `run-L.tif`...).

The resulting images are ingested by the stereo program that computes the matching points in the images and generates a 3D triangulated point cloud:

```
stereo B02_010474_1558_XI_245033W.map.cub B02_010553_1558_XI_245033W.map.cub  
results/out --bundle-adjust-prefix run_ba/run
```

Where “results/out” are the folder/prefix pair created to store all of the files, including the intermediate files produced which can be very useful for checking possible errors or bugs. The `--bundle-adjust-prefix run_ba/run` option specifies where to find the camera adjustments files produced by the `bundle_adjust` process.

The resulting point cloud can be aligned with an existing one. This is important because the point cloud originated by the stereo program, although accurate, can show an offset position on the planet by several meters.

In the specific case, an HRSC DEM is available: `h2493_0001_dt4.img`

(https://pds-geosciences.wustl.edu/mex/mex-m-hrsc-5-refdr-dtm-v1/mexhrs_2001/data/2493/h2493_0001_dt4.img)

`Pc_align` aligns the 3D terrain (the point cloud computed by the stereo program) to a much more accurately positioned dataset, even if of lower resolution (the HRSC DEM):

```
pc_align --max-displacement 2000 h2493_0001_dt4.img results/out-PC.tif --highest-accuracy --save-  
transformed-source-points -o spheroid_DEM
```

The `--max-displacement` option represents the maximum displacement in meters of the source points as a result of alignment. The reason for this option is to remove the possible outliers. `H2493_0001_da4.img` is the name of the HRSC DEM, while `results/out-PC.tif` represents the point cloud originated by the stereo program. In the specific case the option `--highest-accuracy` implies that the calculation is as accurate as possible, even if slower. The `--save-transformed-source-points` option means that the points that after the transformation match the source points are saved. The option `-o` refers to the prefix for output filenames.

The point2dem program originates a DEM and an orthographic image in GeoTiff format from the point clouds:

```
point2dem -r mars spheroid_DEM-trans_source.tif --dem-hole-fill-len 200 --orthoimage-hole-fill-len 50 --orthoimage results/out-L.tif --t_srs "+proj=eqc +lat_0=0 +lon_0=0 +x_0=0 +y_0=0 +a=339600"
```

Where the option -r refers to the datum (Mars in the specific case), spheroid_DEM-trans_source.tif is the point cloud originated by the pc_align program, the --dem-hole-fill-len specifies the maximum dimensions of a hole in the output DEM to fill in, in pixels, the --orthoimage-hole-fill-len specifies the maximum dimensions of a hole in the output orthoimage to fill in, while --t_srs describe the output projection.

The dem_geoid program adjusts the values which are relative to the datum (in the specific case, the Mars sphere) to be relative to the Mars aeroid, i.e., the equipotential surface of the planet.

```
dem_geoid spheroid_DEM-trans_source-DEM.tif --geoid MOLA -o DEM_B02_010474_1558_XI_245033W_B02_010553_1558_XI_24S033W
```

where the --geoid option specifies the geoid to use for the given datum, that in the Mars case is provided by the MOLA MEGDR (<https://pds-geosciences.wustl.edu/missions/mgs/megdr.html>)

Finally, the last command to rename the GIS-ready orthoimage file in the home directory:

```
mv spheroid_DEM-trans_source-DRG.tif ORTO_B02_010474_1558_XI_245033W_B02_010553_1558_XI_24S033W.tif
```

An example of 3D view is shown in Fig. 7.

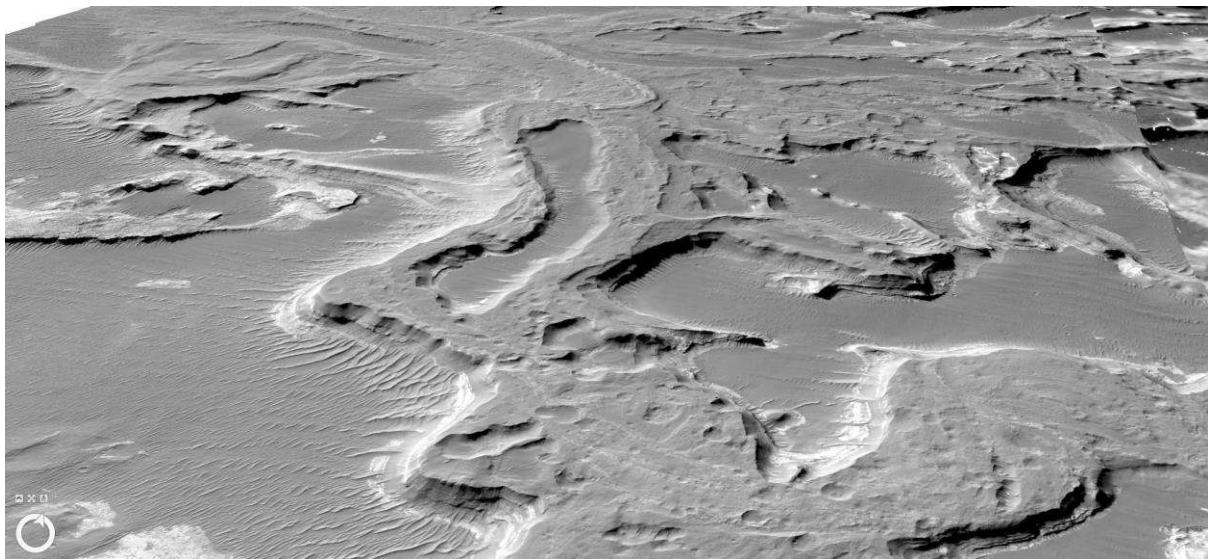


Figure 7 - 3D perspective view of an orthoimage draped over a DEM.

References

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.

Bhattacharya, J. P., Payenberg, T. H. D., Lang, S. C., & Bourke, M. (2005). Dynamic river channels suggest a long-lived Noachian crater lake on Mars. *Geophysical Research Letters*, 32(10). <https://doi.org/10.1029/2005gl022747>

Laura, J., Acosta, A., Addair, T., Adoram-Kershner, L., Alexander, J., Alexandrov, O., Alley, S., Anderson, D., Anderson, J., Anderson, J., Annex, A., Archinal, B.t, Austin, C., Backer, J., Barrett, J., Bauers, J., Becker, K., Becker, T., Bennett, G., ... Young, A. (2022) Integrated Software for Imagers and Spectrometers (7.0.0), Zenodo, <https://doi.org/10.5281/zenodo.6558530>

Malin, M. C., & Edgett, K. S. (2003). Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars. *Science*, 302(5652), 1931–1934. <https://doi.org/10.1126/science.1090544>

Malin, M.C., Bell, J.F., III, Cantor, B.A., Caplinger, M.A., Calvin, W.M., Clancy, R.T., Edgett, K.S., Edwards, L., Haberle, R.M., and James, P.B., 2007, Context Camera investigation on board the Mars Reconnaissance Orbiter: *Journal of Geophysical Research*, v. 112, E05S04, doi: 10.1029/2006JE002808.

Mangold, N., Kite, E. S., Kleinhans, M. G., Newsom, H., Ansan, V., Hauber, E., et al. (2012). The origin and timing of fluvial activity at Eberswalde crater, Mars. *Icarus*, 220(2), 530–551. <https://doi.org/10.1016/j.icarus.2012.05.026>

Pondrelli, M., Rossi, A., Marinangeli, L., Hauber, E., Gwinner, K., Baliva, A., & Lorenzo, S. (2008). Evolution and depositional environments of the Eberswalde fan delta, Mars. *Icarus*, 197(2), 429–451. <https://doi.org/10.1016/j.icarus.2008.05.018>