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Executive Summary / Abstract:

This document explores and illustrates the various possibilities to gather datasets for digital elevation models (DEM) and the creation of digital outcrop models (DOM) . Moreover, the basic steps in the data processing and their meaning are discussed and the most common processing pipelines are illustrated. Finally, we introduce the available open source and commercial tools that can be used to create such models both for planetary surfaces and on Earth analogues and evaluate the different outputs. Examples using actual mission data are provided.

Acronyms and abbreviations

Acronym	Description
ASP	Ames Stereo Pipeline
CaSSIS	Colour and Stereo Surface Imaging System
CTX	ConTeXt camera
CUDA	Compute Unified Device Architecture
DEM	Digital Elevation Model
DOM	Digital Outcrop Model
DTM	Digital Terrain Model
EDL	Entry Descent and Landing
ESA	European Space Agency
EVA	Extravehicular activity
GCP	Ground Control Points
GPU	Graphics processing unit
GUI	Graphical User Interface.
HiRISE	High Resolution Imaging Experiment
HRSC	High Resolution Stereo Camera
ICP	Iterative Closest Point
ISIS	Integrated Suite for Imagers and Spectrometers
LOLA	Lunar Orbiter Laser Altimeter
LROC	Lunar Reconnaissance Orbiter Camera
MarsSI	Mars Système d'Information (Mars Information System)
MDIS	Mercury Dual Imaging System
MER	Mars Exploration Rovers
MOC	Mars Observer Camera
MOLA	Mars Orbiter Laser Altimeter

MSL	Mars Surface Laboratory
MVS	Multi-View Stereo
NAC	Narrow Angle Camera
NAIF	Navigation and Ancillary Information Facility
NAVCAM	Navigational Camera
NASA	National Aeronautics and Space Administration
PDS	Planetary Data System
PILOT	Planetary Images Locator Tool
PLANMAP	PLANetary MAPping project
PSA	Planetary Science Archive
SfM	Structure from Motion
SPICE	**S**pacecraft ephemeris, given as a function of time. **P**lanet, satellite, comet, or asteroid ephemerides, or more generally, location of any target body, given as a function of time, The P component also logically includes certain physical, dynamical and cartographic constants for target bodies, **I**nstrument information, **C**-matrix Orientation information **E**vents
TGO	Trace Gas Orbiter
USGS	United States Geological Survey
VOM	Virtual Outcrop Model
VR	Virtual Reality
WAC	Wide Angle Camera

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Introduction to three-dimensional datasets

Planetary exploration mostly relies on remotely sensed datasets provided by orbital spacecrafts, landers, and rovers. The instruments carried on such platforms are designed to probe different characteristics of the body of interest or to support specific scientific experiments. Among these instruments, imaging systems producing 2D representations of the objects under study are fundamental to the collection of high-quality and readily interpretable data. Imagery is especially important for rover navigation and other engineering or scientific tasks (e.g. to capture images of samples or monitoring the status of a rover itself). As an example, the Mars 2020 Perseverance rover carries more than 20 cameras, used for engineering tasks, science experiments and during entry, descent, and landing (EDL).

Classical images, as most of the camera systems can collect, do not intrinsically provide any kind of information on the three-dimensional nature of the object under investigation. To overcome this limitation additional technologies have been developed with the specific goal of acquiring 3D data. These take the form of active devices, which probe the surroundings using electromagnetic radiation (e.g. light), and passive devices, exploiting stereo vision or other techniques to build detailed depth maps of the environment.

Stereo cameras (see for example Perseverance' Mastcam-Z, Bell et al., 2021) are often used onboard rovers and are constituted by two cameras observing the same scene from a slightly different position (a horizontal baseline separating the two cameras). These systems work by the same principle by which human binocular vision makes it possible to perceive depth.

Elevation maps (Digital Terrain Models - DTMs) are one of the most common products created from orbital imagery, enabling scientists to perform quantitative studies of the imaged morphologies. In this case, two or more images of the same target are acquired from a different point of view, either by an ad-hoc acquisition strategy (e.g. by rotating the camera itself to view the same target from two different perspectives) or as a side effect of normal operations (e.g. partial overlaps during subsequent orbits). The relative positioning of the cameras at the time of the imaging needs to be accurately solved (the baseline is not fixed as for dedicated stereo-cameras) by using navigation data and additional refinements (bundle adjustment).

Active devices are mostly represented by laser-ranging instruments and have been used both on orbiters to build planetary-scale elevation maps (see e.g. the Lunar Orbiter Laser Altimeter, Smith et al., 2010) or to assist spacecraft navigation and mapping small bodies (see e.g. the OSIRIS-Rex Laser Altimeter, Daly et al., 2017).

Additional techniques, especially relevant to space science, can also exploit the intensity of light as recorded by images, to build or refine 3D models. These techniques are known as Shape from Shading or Stereophotoclinometry (Alexandrov & Beyer, 2018; Jorda et al., 2012).

More recently, thanks to advancement in processing power of commonly available computers, in conjunction with new algorithmic developments in the field of computer vision (mostly driven by the needs for three-dimensional data for robotic navigation), new photogrammetric techniques, often referred to as Structure from Motion (SfM) and Multi-View Stereo (MVS), greatly simplified the access to three-dimensional reconstructions for all the physical sciences. Structure from Motion algorithms can accurately reconstruct the relative camera position of multiple images, even for images with imprecise/unknown optical parameters.

These techniques have been promptly welcomed by Earth-based geoscientists (REFS), who appreciated the ability to build three-dimensional representations of outcrops that could be studied even after the in-field investigation. The resulting 3D models (Digital/Virtual Outcrop Models, DOMs or VOMs), other than being made without specialized and expensive equipment, make it possible also to gain access to parts of an outcrop that would be normally of difficult access (e.g. tall cliffs) and can be exploited to obtain a variety of observations and measurements, mimicking the kind of operations that a geologist would perform in the field (Figure 1).

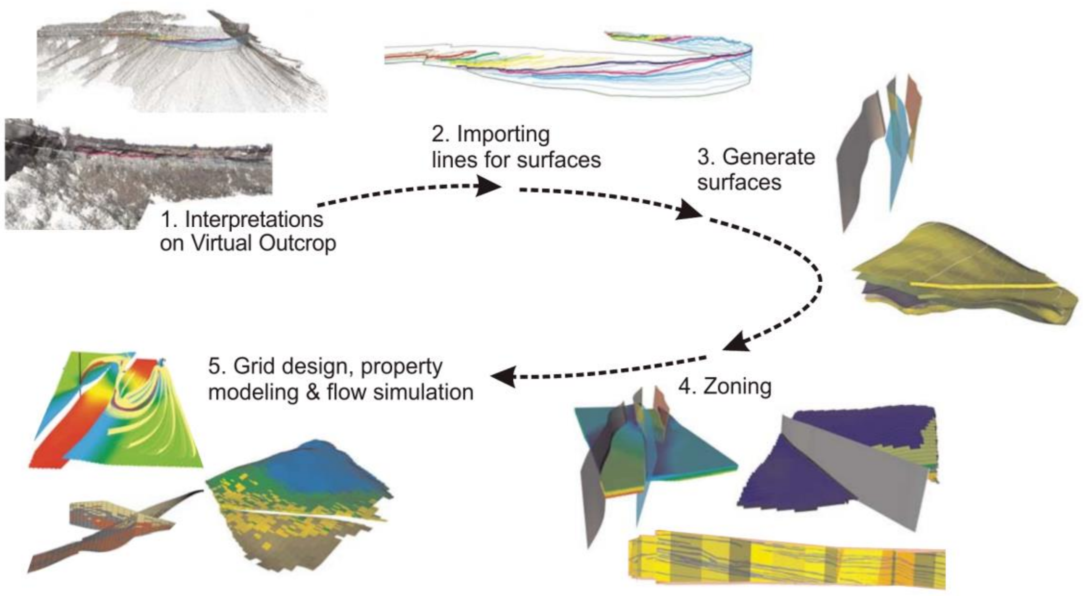

Figure 1: Example case of virtual outcrop models used by Earth geoscientists (Enge et al., 2007). The virtual outcrop model provides a geometrically accurate interpretative framework that can be used to finally set up simulations, e.g. to investigate fluids circulation, especially important for the oil industry.

Similarly, valuable samples can also be subject to three-dimensional reconstructions based on multi-view pictures and possibly integrated with additional three-dimensional information (see for example NASA's Astromaterial website, Blumenfeld et al., 2019)[1].

Furthermore, thanks to the availability of cheap Virtual Reality (VR) headsets, high-quality 3D models are becoming more popular than ever and already demonstrated an impressive potential, in particular for planetary sciences, where the VR technology might provide the best approximation of fieldwork that would be possible only by manned expeditions (Caravaca et al., 2020).

[1] https://ares.jsc.nasa.gov/astromaterials3d

In the next sections, we will provide a practical introduction to a) the generation of elevation models by using stereo imagery (classical photogrammetry, especially useful for orbital imagery) and b) using SfM toolkits for producing 3D models from rover data. This choice was made because thanks to the previously described recent advances these methods can now be employed independently by anybody, without specific knowledge or particularly expensive hardware. This makes it possible to generate completely new products from commonly available imagery.

Both methodologies are already well documented by many sources; hence this document will aim at providing a gentle introduction to the fundamental topics, showcase some examples that the reader could easily replicate on its own, and will then refer the interested reader to the most appropriate literature on the subject.

Imagery acquisition

Stereo photogrammetry is based on the apparent displacement of objects in two or more images (parallax) taken from different points of view. For this reason, a fundamental requirement for the imagery that could be used for photogrammetric reconstruction is to depict the same object as seen from slightly different positions.

Final geometry reconstruction algorithms employ the intensity of light recorded by the images to compute detailed depth maps of the portrayed scene that can then be converted into other three-dimensional formats (i.e. meshes or DTMs). Photometric properties of the imagery (extension of the dynamic range, sensor noise etc) are thus an important factor for the photogrammetric application.

These two requirements (observations from different locations and good photometric properties) lead to a possibly long list of suggested "optimal" conditions that can be rarely fully respected when dealing with planetary data. Although the imaging devices used in exploration missions are of extremely good quality (in terms of resolutions and dynamic range) the other conditions can be rarely controlled and must face the limitations imposed by mission operations.

In particular, SfM methods, being designed to operate without restrictive acquisition geometries and technical requirements can be used to build 3D models even from imagery that was not specifically acquired for that aim, making it possible to leverage also "old" imagery for novel quantitative analysis.

Taking inspiration from the recent work by Le Mouélic et al. (2020) we will demonstrate the application of SfM on some of the same datasets presented in their work, specifically on Apollo 17 imagery collected by the astronauts on the lunar surface.

Rover imagery from Mars constitutes a particularly good source of multi-view imagery that can be easily used in conjunction with SfM toolkits for building three-dimensional DOMs. A case based on Curiosity’s MastCam images will be demonstrated in the next sections.

Datasets that could be used for DEM generation from orbital imagery are of great variety and are specifically acquired to the aim (HiRISE, HRSC, CaSSIS and MOC for Mars, LROC NAC and WAC for the Moon) or resulting from overlaps in observations during consecutive orbits (CTX on Mars). Useful tools for searching and selecting stereo imagery are the Orbital Data Explorer from NASA-PDS[2] and PILOT from USGS[3], where stereo coverage of a pre-selected area can be evaluated in terms of stereo angle, area covered by stereo observation and expected vertical precision in the DEM.

ESA missions are in some cases mirrored into the previous services, although for specific missions such as Rosetta and Exomars TGO the data repository is the ESA PSA (Planetary Science Archive)[4].

For rover imagery there are different sources to consider, but essentially most of the dataset from Curiosity/Mars Exploration rovers can be easily found by using the Analyst's Notebook[5] . It is a service toolset useful for accessing science archives from NASA landed missions (i.e. landers, rovers, and historic Apollo EVA stations). It contains images, panoramas, and traverse paths with stations for analysis and access or link to data repositories.

Orbital/aerial stereo-photogrammetry

To illustrate the classical stereo photogrammetry, we take as example a typical pipeline used in planetary science or for Earth-based satellites. It integrates the use of ISIS (integrated Software for Imagers and Spectrometers (Gaddis et al., 1997) for data import and calibration, commonly used in planetary science, and ASP (Ames Stereo Pipeline (Beyer et al., 2018). The following process can be automated locally via bash scripting/python wrapping or through the use of the MarsSI portal[6] for cloud processing in a semi-automatic manner (Quantin-Nataf et al., 2018).

Images preparation in ISIS

Raw camera files come in PDS file format and need to be translated into ISIS3 (Gaddis et al., 1997, Integrated Software for Imagers and Spectrometers, from USGS) format (.cub). Pre-processing steps can involve radiometric calibration if needed, destriping/despiking and are usually well-documented into the ISIS3 software manual.

At this stage, an image is just a 2D matrix of pixels. The software does not know any geometric information, neither camera parameters, nor pointing on the surface of the planetary body.

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[2] https://ode.rsl.wustl.edu/
[3] https://pilot.wr.usgs.gov
[4] https://archives.esac.esa.int/psa/#!Home%20View
[5] (https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx
[6] https://emars.univ-lyon1.fr/MarsSI/

To proceed in the stereo matching the correct SPICE kernel information needs to be attached to the specific image pair.

SPICE kernels

In planetary science, and in particular to that related to orbital observation, the SPICE kernels are fundamental as they contain navigation information from the satellite on which the camera is onboard and other ancillary information providing precision observation geometry, camera optical and calibration parameters (e.g. pointing, position above the planet, source. NAIF-JPL, NASA).

Each mission possesses its own spice kernels related to instrument observations that need to be handled in order to locate the observation correctly on the planetary surface. SPICE kernels can be downloaded locally for each of the main orbital planetary missions or used through a web service from command line or user interface of ISIS (Figure 2).

At this step, the image has correct pointing and camera model in its metadata and can be used for further processing.

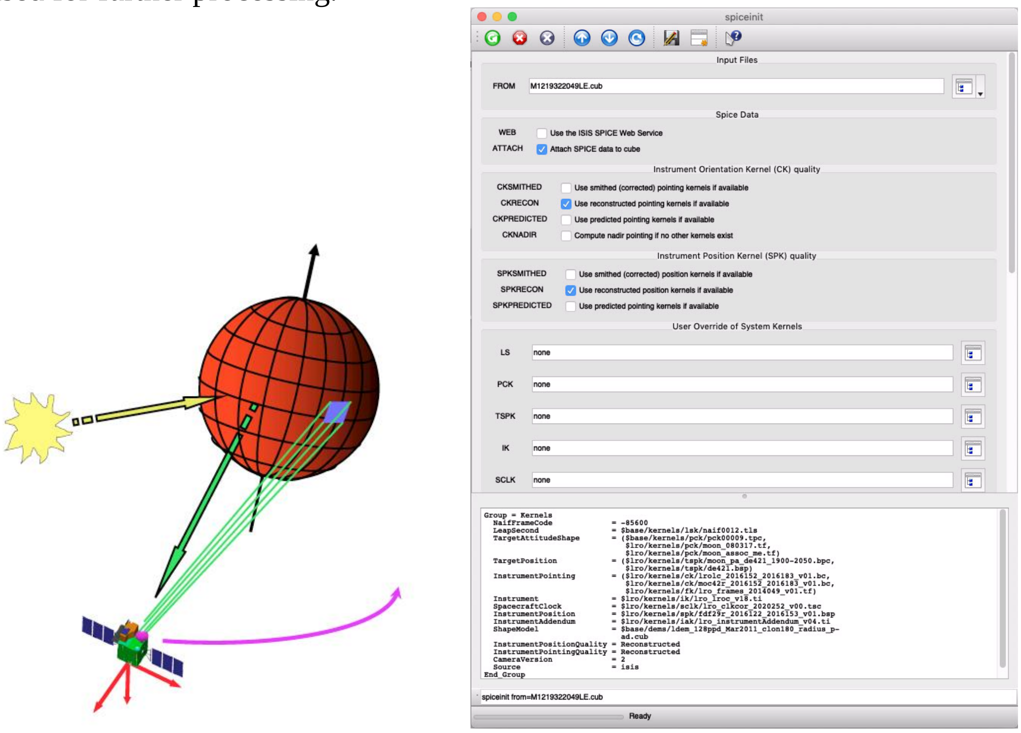


Figure 2: Schematic representation of one of the functions of SPICE kernels useful for image location on a planetary surface and graphic user interface for spice kernel attachment to a LROC NAC image in ISIS.

Bundle adjustment

It is an iterative process used to minimize the errors of pointing and positioning of the camera while observing the same feature or object from multiple positions. It essentially ensures internal self-consistency in the observations and corrects the position and orientation of the cameras and also of the observed object in the 3D space as soon as self-consistency is reached (see Figure 3). This concept takes advantage of all the images available and can also use a priori known feature positions in the form of GCPs (Ground Control Points).

Bundle adjustment can (and should) therefore be used both for stereo photogrammetry from aerial/satellite and also for DOM creation through SFM, as it is a tool that validates the dataset to perform quantitative scientific analyses and not only visualization (Figures 3, 4, 5).

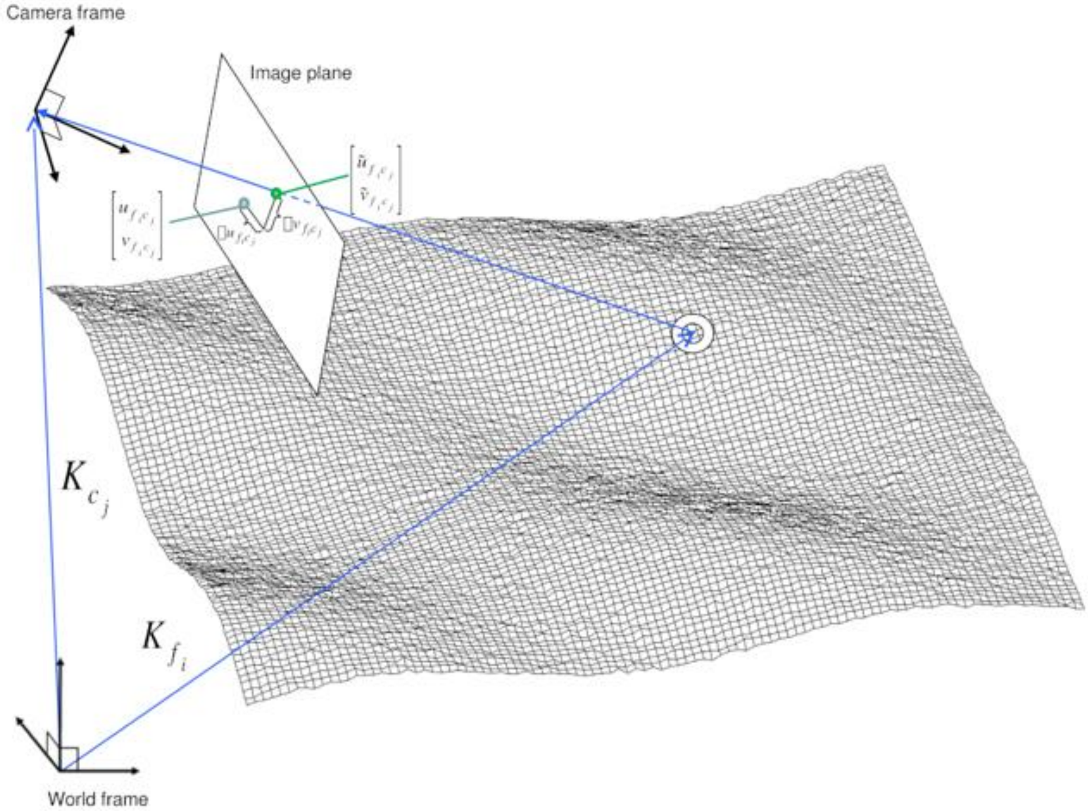


Figure 3: Feature observation during bundle adjustment, source: Moore et al. (2009).

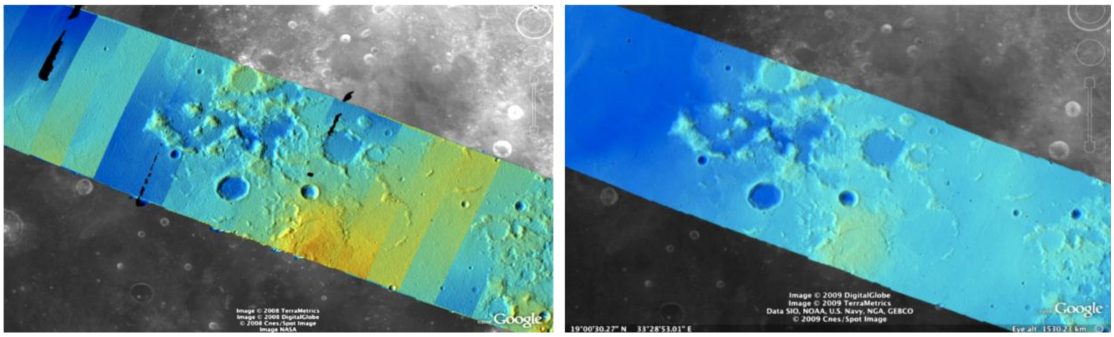


Figure 4: Mosaic of stereo DEMs from Apollo 15 orbit 33 camera before and after bundle adjustment. Seamlines and differences in height are clearly visible, and almost absent in the bundle adjusted DEM. Source: Beyer et al. (2018), ASP manual (https://stereopipeline.readthedocs.io/en/latest/bundle_adjustment.html)

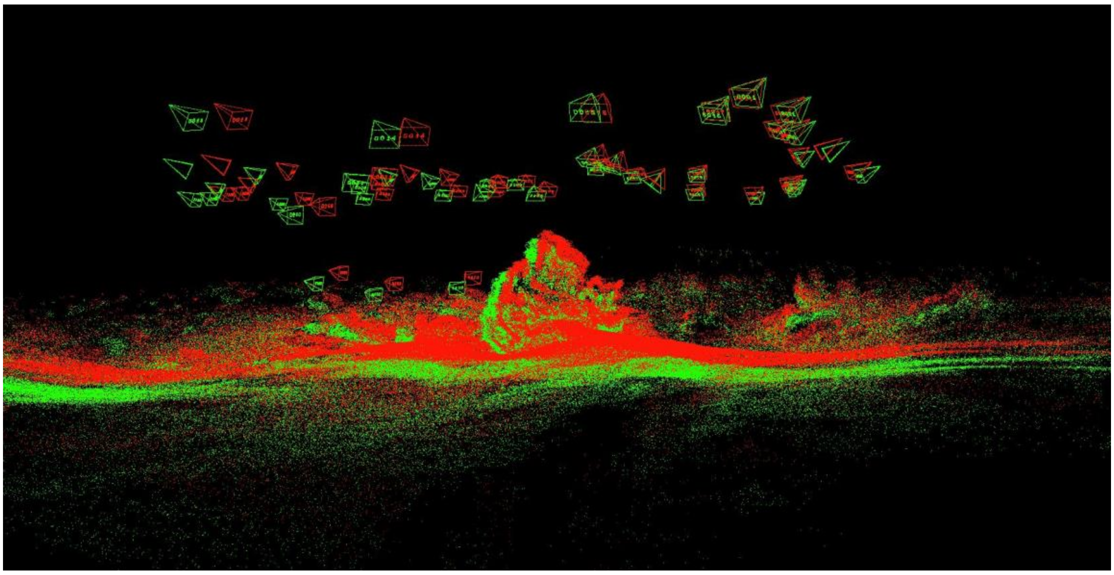


Figure 5: Bundle adjustment in a sparse cloud during a DOM generation of a rock outcrop in a volcanic lunar analogue terrain, realised in MicMac. In the top part camera pointing and position in 3D space are visible. In red camera position guessed by the software in the first sparse cloud generation and in green the corrected position and new point cloud generation after bundle adjustment. Slight to large shifts in camera positions can be seen in the top image part and slight shift in the point cloud as well.

Map projections

Stereo correlation automatically aligns the left and right image pair using a number of options, the latter of which can be map projection.

There are cases in which bundle adjustment is not able to provide a correct solution to the camera and object self-consistency problem. This could be due to a number of factors: bad illumination conditions, absence of clear features and/or a smooth terrain, poor or degraded image quality. In this case the images, thanks to the SPICE kernels can be map projected using the correct planetary datum (see ISIS guide https://isis.astrogeology.usgs.gov/Application/index.html#Map_Projection) and then map projected images can be used as input for stereo matching, although self-consistency and scientific significance can be degraded or sub-optimal.

Stereo correlation

This process can in reality be broken down in 5 main sub-processes as shown in Figure 6. It essentially computes a disparity map which is a map of correspondent pixels between left and right image (Figure 7), leading to triangulation and production of a point cloud.

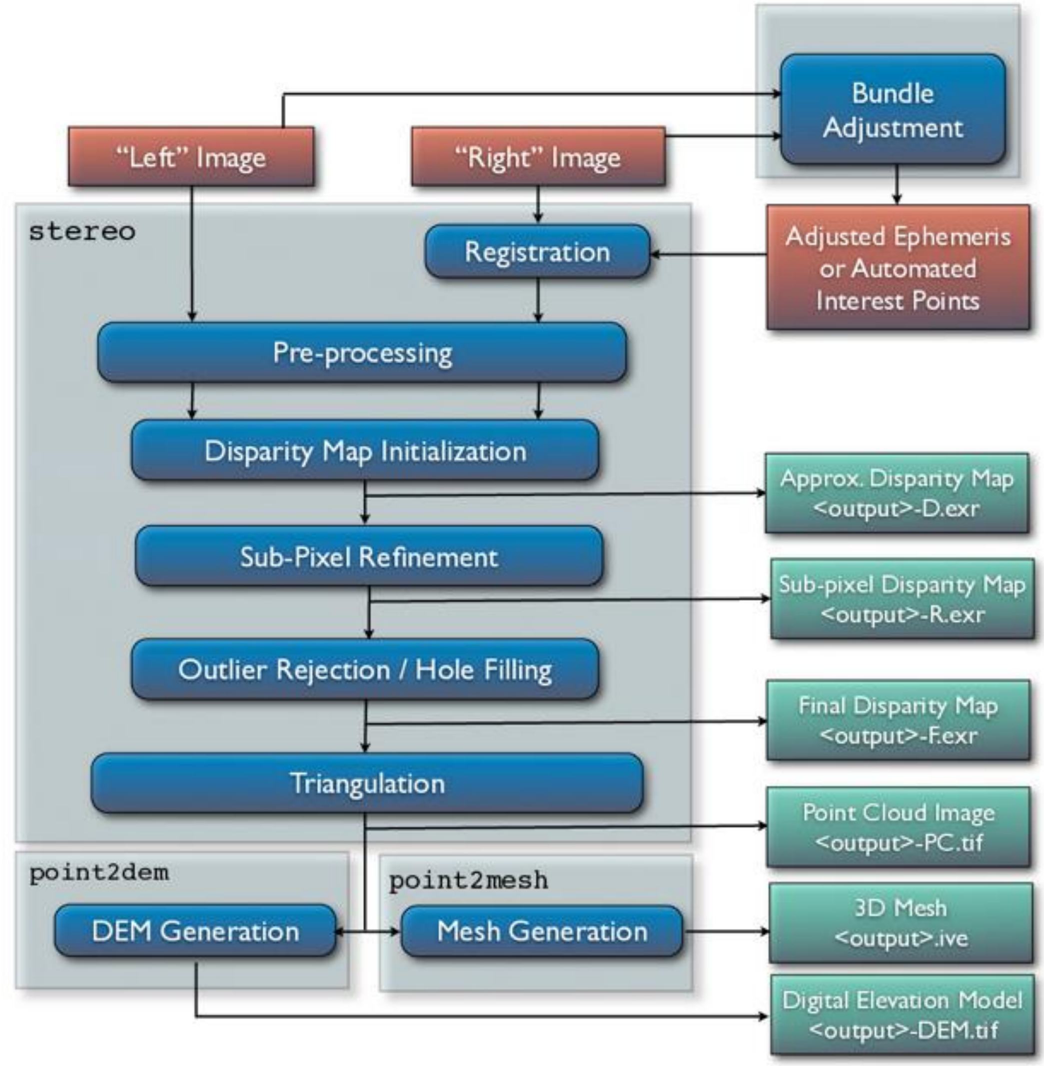


Figure 6: Stereo pipeline general workflow. The stereo block contains 5 different processes that enable reconstruction of the depth map and point cloud triangulation from 2 stereo images before DEM and Mesh generation. Source: Beyer et al., 2018, ASP guide[7].

[7] https://stereopipeline.readthedocs.io/en/stable/correlation.html

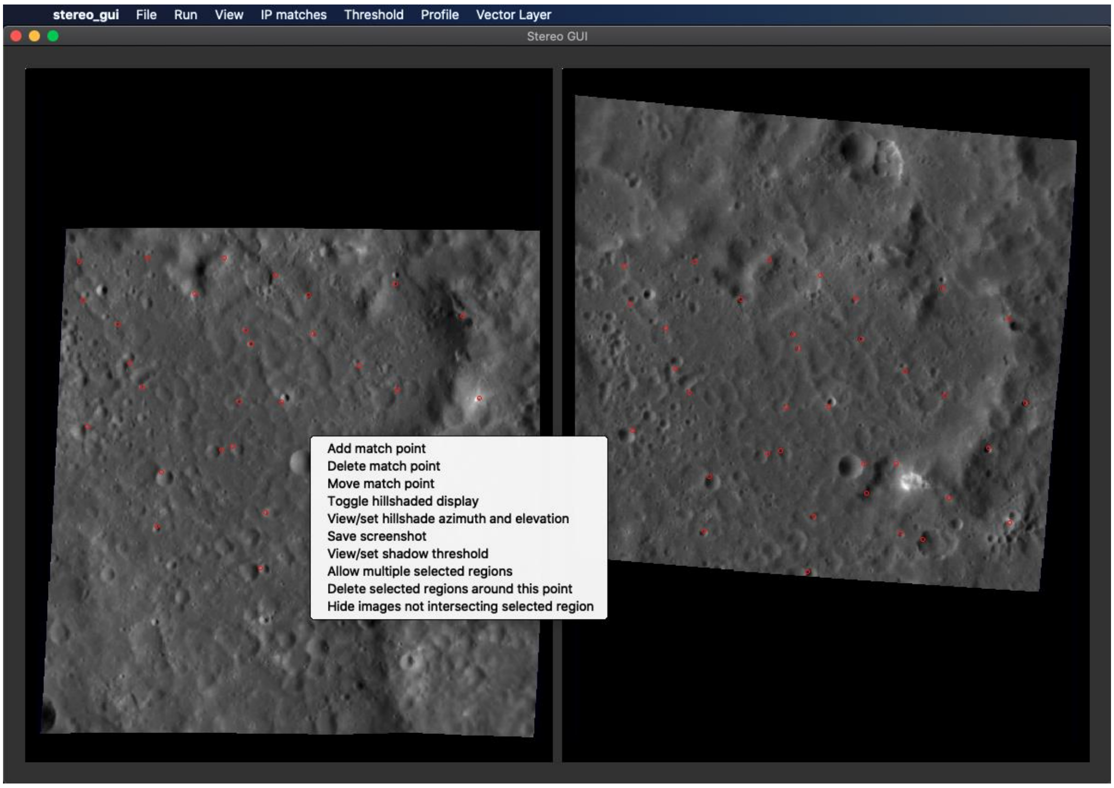


Figure 7: Example of the stereo GUI showing two frames of MESSENGER MDIS of Mercury's surface, with a contextual drop-down menu in white for manually adding matching points, shadow thresholds and other editing options. In red are visible manually added matching points.

Point cloud registration

Point cloud registration is very important when working with multiple datasets coming from different sources, or if the aim is to merge multiple ones. This step has to be run prior to DEM interpolation and is based on ICP (Iterative Closest Point) algorithms. It requires an input point cloud and one or multiple reference DEMs (can be laser reference global topography such as MOLA for Mars and LOLA for the Moon) in the form of raster or point cloud (also in .csv format). It adjusts the input point cloud on the reference DEM/point cloud trying to match them, adjusting scale, rotation, and translation, and using feature-based matching as well.
A maximum expected displacement can be set in order to get rid of those outlier points that are way farther than this value, and that could degrade the final result.
This step is really well-documented here:

https://stereopipeline.readthedocs.io/en/stable/tools/pc_align.html?highlight=pc_align#pc-align

DEM interpolation and orthomosaic generation

Such aligned point cloud can now be either meshed or interpolated in a raster with a definite cell (pixel) size. A best practice is NOT to set the cell size equal to the image resolution, as a pixel-per-pixel tie points detection is not possible or difficult and may generate errors. Instead, a good rule of thumb is to set the cell size of the DEM 3x or 4x larger than the image resolution. The software then takes the point cloud and interpolates the values generating a grid of pixels of a defined size, whose value represents the height value. Orthoimage and/or orthomosaic generation is the process to correct the distortions and apparent changes of the position of objects on the ground caused by the perspective of the observation angle and the terrain morphology. Orthorectification takes this into account all this information and deforms/adapts the image to perfectly match the topographic information/3D morphology.

Orthorectified images are therefore reliable as they return the real match of image with 3D objects and is highly recommended for GIS analysis. Moreover, orthorectified images can be used as textures for DEM-derived meshes and visualized in full 3D environment.

Shape-from-shading

This technique is frequently used to enhance the fine details of the DEMs where the stereo matching algorithm is not able to do that. It can be due to a number of reasons, among which the main is a too homogeneous or smooth terrain with subtle tone variations, like for example a smooth lunar maria region with small impact craters (see Figure 8). Shape from shading uses the illumination conditions of one (or multiple) images of the same area in order to derive the convexities and concavities of the surface defined by the shading in the images themselves.

Shape from shading is typically highly computationally expensive and does not always provide a best solution or a high-quality result. It is highly dependent on illumination conditions, and in particular to the presence of hard shadows or oversaturated image portions. It typically works well where the terrains have features with low topographic gradients.

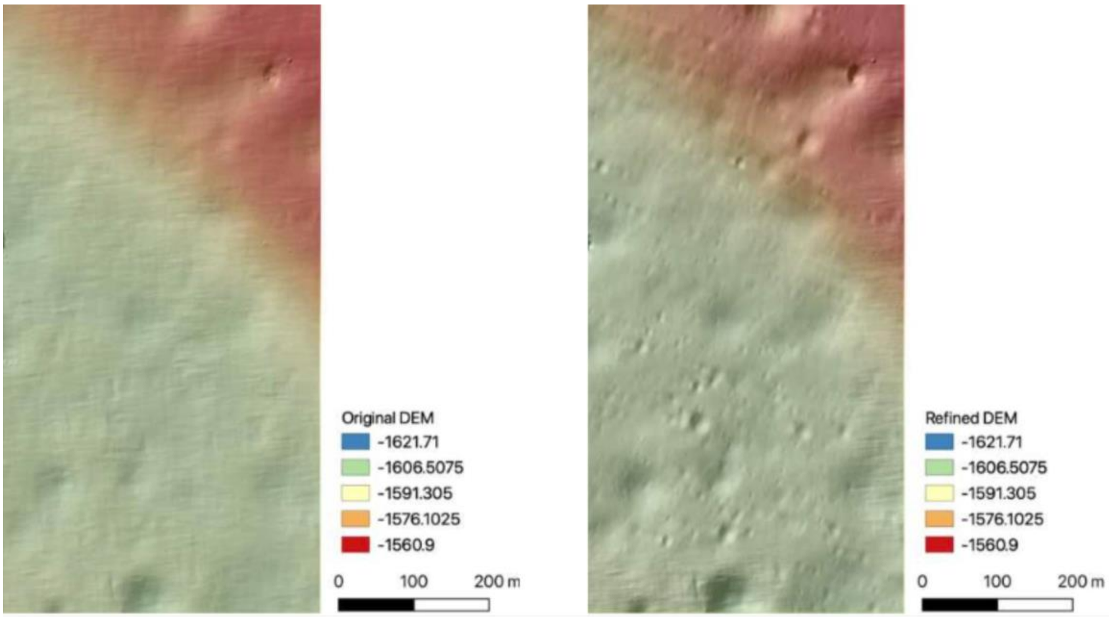


Figure 8: DEM from LROC NAC stereo images of a smooth lunar maria terrain colour coded with shaded relief in transparency. On the left panel it is visible the poor detail

and the presence of artifacts, on the right panel the DEM after the application of shape from shading technique to enhance fine details.

Overall description of the pipeline required for SFM

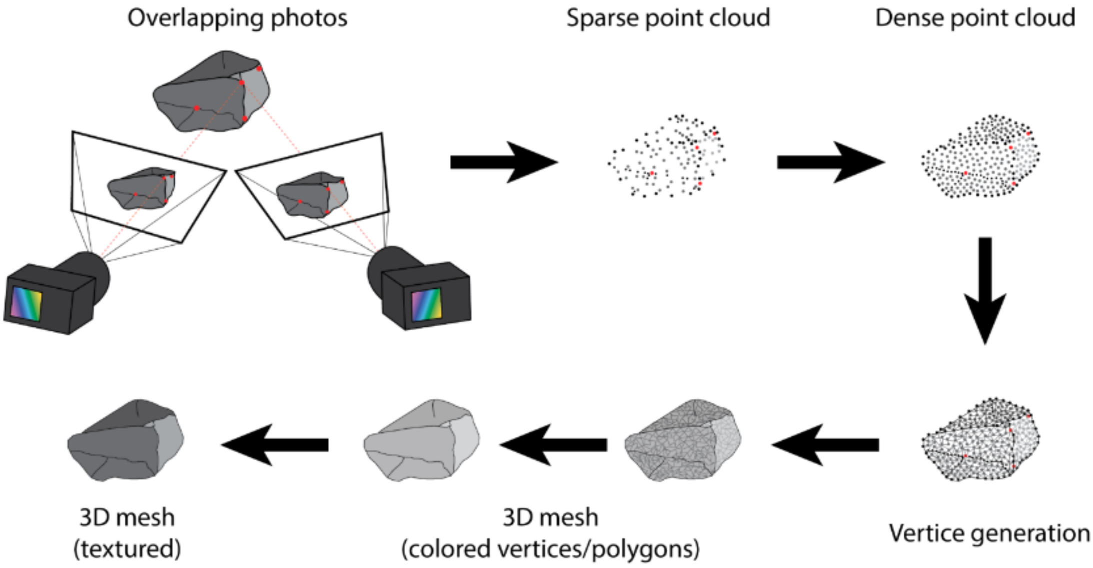


Figure 9: Workflow for photogrammetric reconstruction with structure from motion, using multiple overlapping observations of the same object from different points of view. The software detects similar tie points across each image from different points of observation and projects them into 3D space (either in local or geo-referenced coordinates). Then the first sparse point cloud is densified and is triangulated into a polygon mesh, textured with the original images that are mosaicked seamlessly together. This procedure is common to every structure from motion software and is not dissimilar to that used for stereo-photogrammetry. Image and caption from PLANMAP D5.2, Caravaca et al. (2019).

1. Image upload, colour calibration, white balance calibration
2. sparse cloud generation with Tie points thresholds (depending on the level of detail desired)
3. Bundle adjustment
4. Sparse cloud cleaning and filtering to remove outliers
5. Dense cloud generation
6. Mesh generation
7. Texture generation
8. DEM interpolation
9. Orthoimage generation

Scaling, geographic localization and models co-registration

Photogrammetric methods, especially in their SfM-based incarnation, are appealing because their unique “hard” requirement is to have a set of pictures of the same object at hand, taken from multiple points of view. All other requirements tend to be softer and interesting results can be obtained also in difficult conditions. On the other hand, these methods cannot provide several important pieces of information on their own.

The units or measure of a three-dimensional model reconstructed by SfM are in general arbitrary and the scaling and orienting of a model requires additional layers of information. These can be provided in different ways, also depending on the software used for 3D reconstruction. The same happens for localizing a model in terms of absolute geographic placement: reconstruction software is in general unaware of the specific geographic location and the model is built in an arbitrary reference frame.

These issues can be solved by providing enough information prior or during bundle adjustment (or SfM) in the form of precise locations of the cameras (e.g., by using SPICE kernels) or by providing the 3D coordinates of known points visible in the imagery. The specific procedure is highly software-dependent, and the reader should refer to the documentation of the software of choice. Notice that not many open-source toolkits provide this option (e.g., MicMac and ASP do provide these features).

Alternatively, the model can be scaled and oriented after reconstruction, by using elements with known length (for scaling) or orientation. A common approach is to use an already existing dataset (e.g., a DTM) which is known to be correctly located and scaled to co-register the new 3D model, CloudCompare provides an open-source solution for this specific task.

Image masking

Masking images for photogrammetry is a particularly useful tool when used for DOMs but they can have applications also on stereo photogrammetry from satellite images (e.g. to remove hard shadows from images in order to improve the quality of the stereo reconstruction, see also shape from shading chapter for more details).

Masking images is a non-destructive technique to hide unwanted portions on images and show only the portions we want to work with.

In photogrammetry, masks are used to separate the object in the foreground from the background with multiple benefits: avoiding tentative correlation from the SFM software trying to reconstruct portions of the background, reduction in precision in foreground reconstruction, generation of artifacts, reduce the time required for calculations just to the wanted object.

A mask is simply an overlay layer, alpha channel, or image with binary information, all the unwanted portions of the image are set to 0 and to 1 (or non-zero in particular cases) the wanted portions. This can be achieved with almost every software that handles raster graphics, but masking routines are often embedded also within the photogrammetry software packages.
However, it must be noted that not all the software packages discussed in this document are able to use masking.

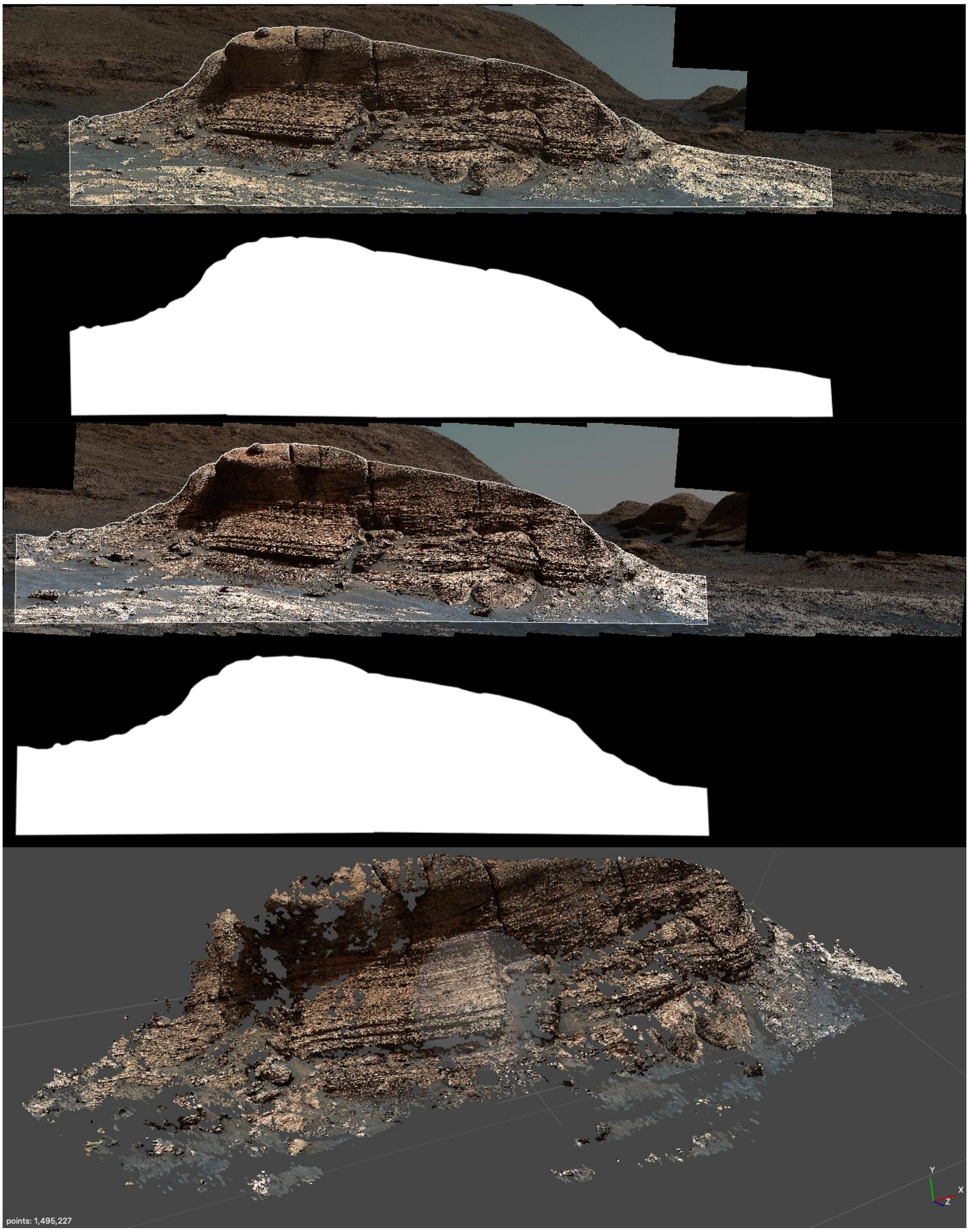


Figure 10: Example of a DOM obtained from 2 stereoscopic mosaics from Curiosity Mastcam images (PIA24266) using Metashape. in a ,b, c, d) the two mosaics are masked in order to use only the image information in the foreground (the white portion in the image masks). Important notice: as the images are quite detailed and with a sufficient stereo angle to provide enough parallax for a depth map, the software tries to guess the camera parameters if they are not contained in the metadata. In the case of image mosaics like this, the model can be built but there is little or no control on the correctness of its size/measures.

Point cloud filtering

As photogrammetric software capabilities are increasing for dense image matching producing extremely dense point clouds, artifacts and outliers are also more frequently present and need to be removed in order to produce a reliable DEM/DOM/VOM to be then used for scientific and visualization purposes.

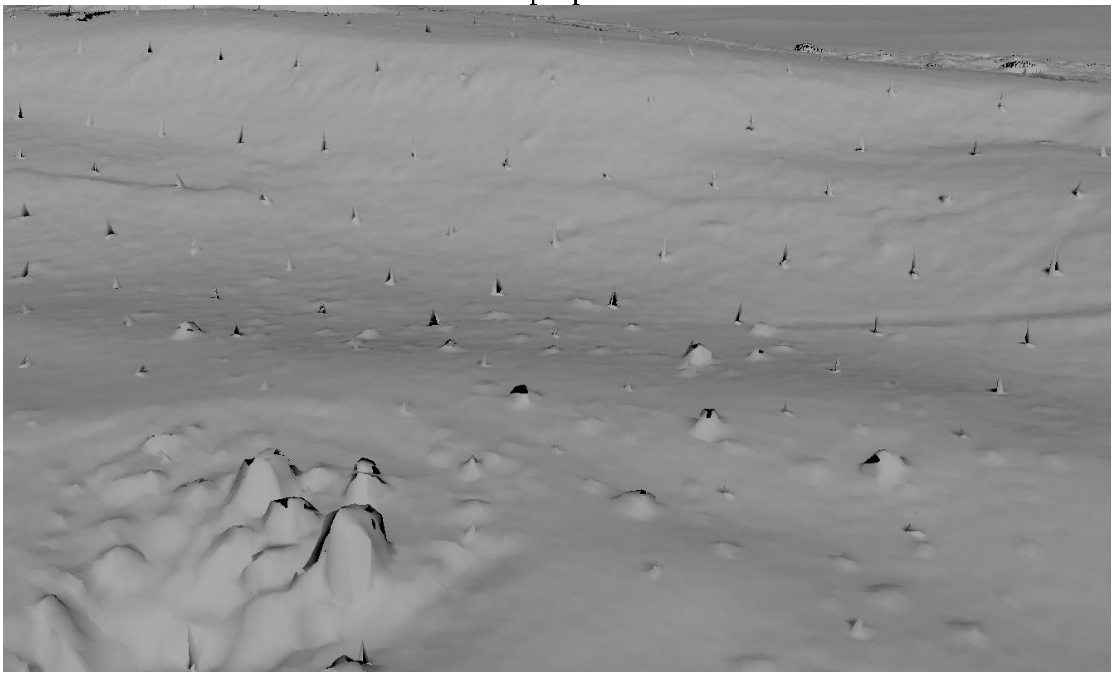


Figure 11: Systematic error in a mesh resulting from a drone survey in the form of arrays of spikes of the same size on a terrain. Outlier filtering can help mitigate the problem that could severely affect the quality of the final dataset.

Meshing and texturing/UV mapping

Textured meshes are a common format for sharing and visualizing three-dimensional models. Online platforms and desktop applications are often designed to take full advantage of these formats (see as an example the Sketchfab platform), rather than working with point clouds.

It is important to notice that in most of the cases the results of dense image matching, which is commonly used in stereo photogrammetry, is in the form of point clouds rather than higher level or structured (e.g. raster) formats, meaning an additional conversion is often made to generate the final product in the form of meshes.

Triangular meshes are a numerical representation of a surface that is achieved by providing two levels of information: first the points (vertices) forming the model are listed and then the vertices are grouped in triangular faces by listing the ids of the vertices that forms each triangular face. Similarly, non-triangular faces can also be constructed (e.g. quad-based meshes).

The dense point clouds produced by cross correlating stereo imagery can be transformed into meshes by employing triangulation algorithms. Among many different options, a commonly implemented algorithm is the Delaunay triangulation, which tends to produce good results without additional user input.

An important observation that should be kept in mind when working with meshed point clouds is that those are linear interpolations of the available points. The meshing process does not add new information in terms of geometry reconstruction and can be sometimes misleading by producing fully meshed surfaces even when little or no geometric data (vertices) were originally present in the point clouds. This might impact especially scientific analysis requiring measuring local geometric properties (e.g. measure local attitudes for structural studies). To this aim it might be sensible to also use and/or visualize the original point clouds.

A major advantage of meshed surfaces is the possibility to associate colour (or also other kind information) not only to each vertex (or triangle), but high-resolution imagery can be packed together with the mesh and then visualized by most 3D visualization software. Also, in this case it should be noted that the geometric resolution of the mesh is often lower in respect to the resolution of the associated textures. This issue should be kept in mind when performing interpretation using the textures as a basis.

Textures, which are just one or more common raster images, are associated to their mesh by means of additional scalar fields that are computed, during the texturing process, for each vertex of the model (UV coordinates). Intuitively, these scalar fields represent the coordinate of each vertex in the respective texture image. Then the visualization software uses this information to interpolate the colour data on the triangles in the right location.

Although the original pictures could be easily used to produce a texture, this solution often does not produce satisfying results, especially on objects with complex geometries (e.g., VOMs), but might work well for 2.5 D scenes (as in most DTMs). Most 3D reconstruction software employs quite complex algorithms taking into consideration all the available points of view and will try to produce a synthetic image composed of different patches of optimally-selected imagery. An example is shown in Figure 12.

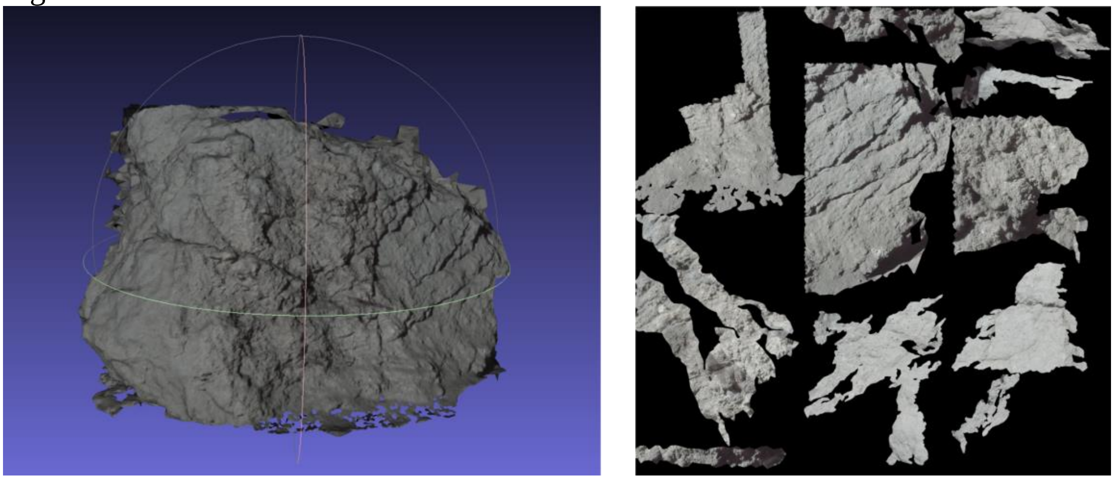


Figure 12: Example of a textured 3D model and one of its associated texture files: pieces of information from all the cameras are packed together into a single image. UV coordinates, associated to each mesh vertex, are used by visualization software to correctly map the texture onto the model. Depending on the texturing algorithm the

software is using one or several textures might be generated. Also, the layout in the texture files will vary.

Available toolkits:

ASP - Ames Stereo Pipeline

ASP stands for Ames Stereo Pipeline, and it is a free open-source software produced by NASA-Ames designed specifically for stereo reconstruction from planetary and Earth satellite, rover-based stereo images, aerial and historical images. It is capable of producing DEMs, orthoimages and orthomosaics, point cloud alignment and point cloud mosaicking, bundle-adjusted control networks. It integrates effectively with ISIS 3 as it is able to ingest (but not limited to) ISIS formatted files (.cub).
Although it is well-integrated with ISIS routines for planetary orbital data treatment it works well in a variety of contexts, such as with framing, pinhole, and panoramic cameras and also with scanned aerial/historical images. It is able to perform bundle adjustment, point cloud registration, textured mesh generation, DEM and orthoimage and point clouds merge.

Although it is more oriented to command line usage, scripting and wrapping, it also has GUI applications for specific tasks such as stereo correlation, GCP manual and auto detection.
It can also be set to work on computing clusters using GNU parallel for process parallelization.
In general, it works on Unix-like systems such as Linux distributions and Mac OS, or on the Windows Linux subsystem.

It is available for download at its GitHub page, and it comes with a very detailed manual illustrating all the main use cases, from planetary mission data with multiple examples, to earth satellites data to rover-based stereo matching.

The software can be downloaded at this link:
https://github.com/NeoGeographyToolkit/StereoPipeline

And the manual is available at the following link:
https://stereopipeline.readthedocs.io/en/latest/

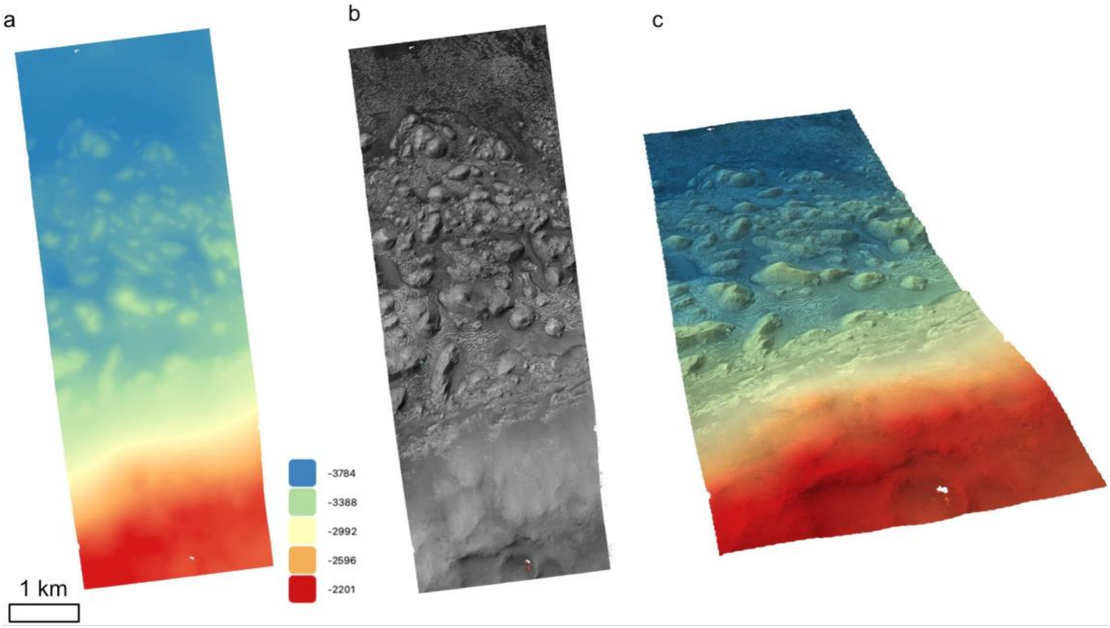


Figure 13: Example dataset from ASP stereo DEM generation using a HiRISE image stereo pair (ESP_026270_1820, ESP_027747_1820). In a) the interpolated DEM at 1m of grid size with color-coded height values, in b) the orthorectified left image of the pair and in c) perspective view of the DEM textured with the orthoimage.

Meshroom

Based on the AliceVision framework[8], it provides a simple and effective interface to a variety of algorithms for SfM, dense depth maps generation, meshing and texturing. These algorithms can be chained together in a visually appealing graph editor making it possible to generate ad hoc and complex pipelines without the need of knowing any programming language (Figure 14). Preconfigured pipelines greatly simplify the technical knowledge necessary to produce 3D meshes.

The software also supports distributing the workload on already existing render farms[9]. Thanks to the simple and clear interface this is possibly the best solution for practitioners with little or no technical background in SfM.
At the moment, dense cloud generation, stereo registration and meshing is available only using NVIDIA GPUs with CUDA enabled.

[8] https://alicevision.org
[9] https://github.com/alicevision/meshroom/wiki/Renderfarm-submitters

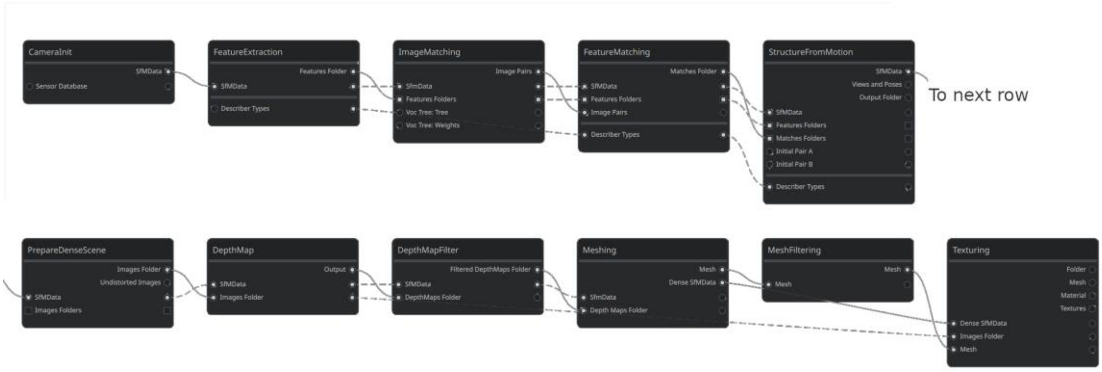


Figure 14: The preconfigured pipeline for SfM-based reconstruction allows to quickly start new projects without complex setups. Customization can then be added to the pipeline by inserting new computational blocks, splitting the pipeline to experiment with different setups or by modifying the parameters for each block.

An exemplary result of the default pipeline with minor adjustments is portrayed in Figure 15. This toolkit can produce impressive results without user supervision. Thanks to a well-developed caching mechanism result from previous runs are always maintained making it possible to experiment with alternative pipelines without losing previous results.

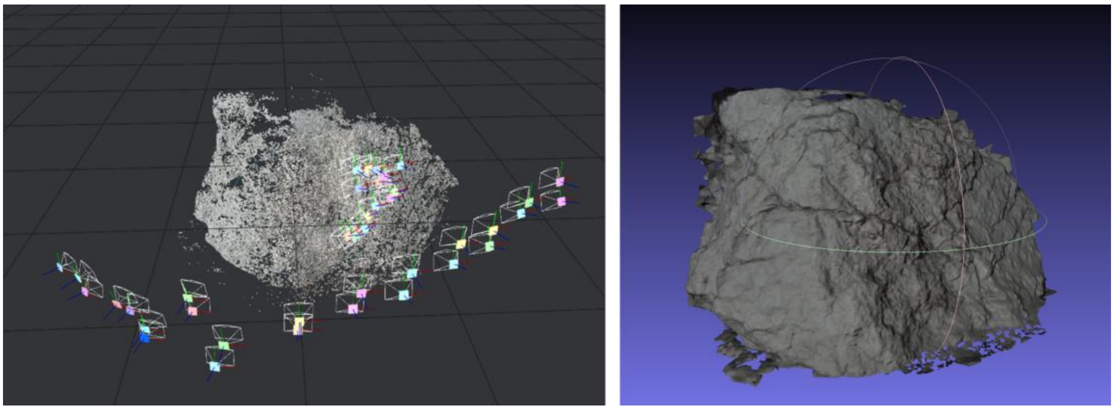


Figure 15: Left, the results of SfM on 40 Apollo 17 images for a boulder. The resulting 3D DOM computed by meshroom.

Results from meshroom are mostly comparable with results obtained from specialized commercial software (see for example the paragraph on Metashape), although some commonly used operations (e.g. easy image masking or manual tie points definition) are still missing or incomplete.

COLMAP

COLMAP is an open-source general purpose structure from motion and multi frame dense matching software. It is cross-platform and works on Windows, Linux, Mac OS and comes with pre-built binaries or can be built from source code.
It can be used via command line or graphic user interface, and is able to produce sparse clouds, dense clouds, meshes with 2 different interpolators and textures. It is also able

to make use of image masks for better dense matching and GPU computing for speeding up the processing time.
COLMAP, as almost every other software has a pre-built general pipeline for model generation from structure from motion, although several parameters can be tweaked as the process can be broken down in different steps.
At the moment like on Meshroom, dense cloud generation, stereo registration and meshing is available only on Windows platform with NVIDIA GPUs with CUDA enabled. Pre-built packages of COLMAP do exist for Linux, though, in addition to the possibility of building from source.

It can also produce video files of the matching in progress, showing the point cloud during its construction and the camera frames being added as soon as they are computed in the matching process.

It can be installed from:

https://demuc.de/colmap/

And the software manual, example datasets and use cases are at this link:

https://colmap.github.io

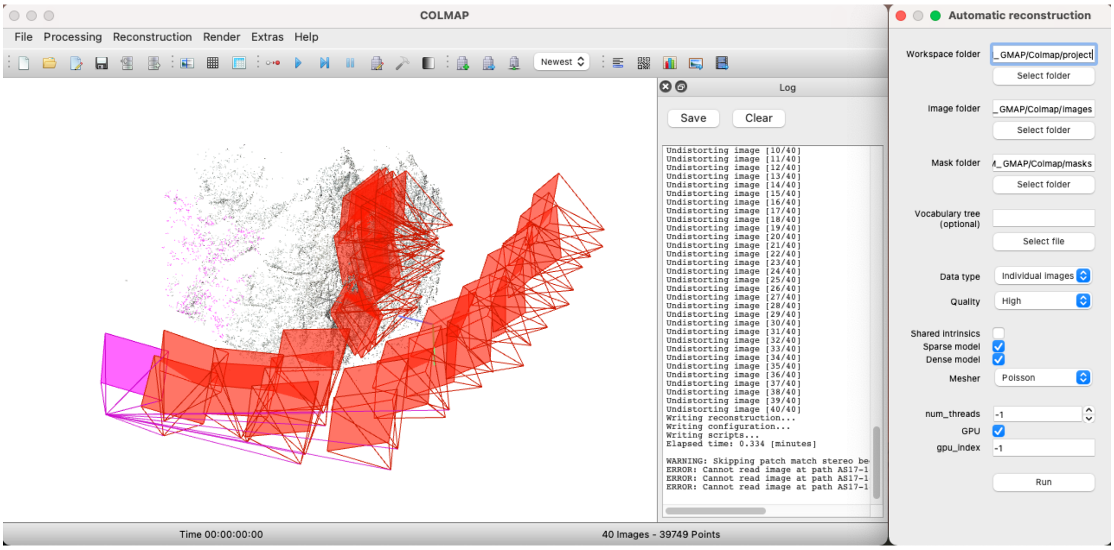


Figure 16: Example of the main COLMAP user interface and controls with displayed a sparse point cloud of a lunar boulder from Apollo 17 astronauts' EVA scanned photographs. In purple a selected camera with its orientation, the frame and the point cloud portion related to the observation of that camera. In the right menu is visible the project folder for the working files, the image folder, and the mask folder. The outputs can be chosen to be sparse and/or dense point clouds. GPU computing can be enabled (also for non-CUDA GPUs for sparse cloud reconstruction).

MicMac

MicMac is a free open-source software package used for multi-purpose 3D reconstruction from structure from motion. Its strength is its flexibility as it is capable of generating DOMs, DEMs and orthoimagery in local or global coordinates.
It comes with a pre-built pipeline for generic model creation or can be broken down in different steps with different commands, useful for checking different steps, hand cleaning point clouds, etc.

The software is presented here:
https://micmac.ensg.eu/index.php/Accueil

It can be installed in Unix-like systems such as Linux distributions and Mac OS, Raspberry Pi and Windows. Although it is command line based it also comes with a GUI that needs to be set up separately from the software upon request to the developer.All the installation instructions can be found here:
https://micmac.ensg.eu/index.php/Install

Tutorials encompass different use cases from DOM with reflex cameras, with targets for photogrammetry, aerial with geographic reference system information to be embedded and structure from motion from video frames. Test datasets are also provided. Tutorials are constantly added and translated from French documentation. All the material can be found here:
https://micmac.ensg.eu/index.php/Tutorials

A list of MicMac main commands and their meaning can be found here:
https://micmac.ensg.eu/index.php/MicMac_tools

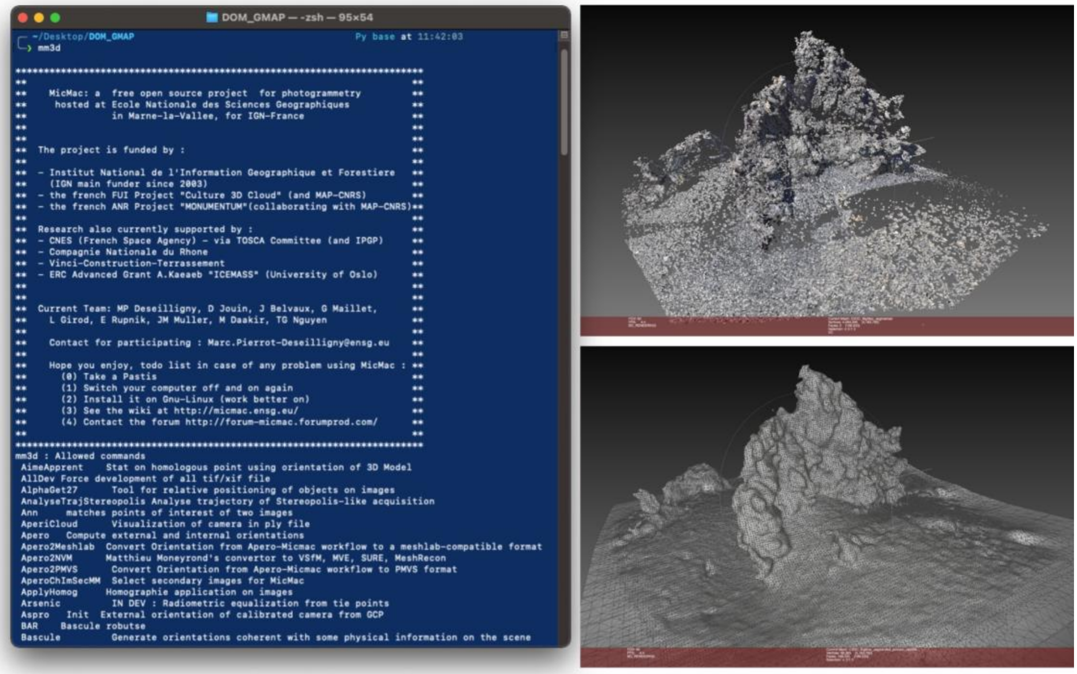


Figure 17: Example of the command line main interface of MicMac, b) point cloud and c) mesh of a DOM visualized in Meshlab software.

Regard3D

Regard3D is an open source gui-based software for SfM, dense cloud, mesh, and texture creation. It is cross-platform, working on Windows, Linux, and Mac OS.

Installer and documentation can be found here:
https://www.regard3d.org/index.php

Documentation and tutorials:
https://www.regard3d.org/index.php/documentation/tutorial

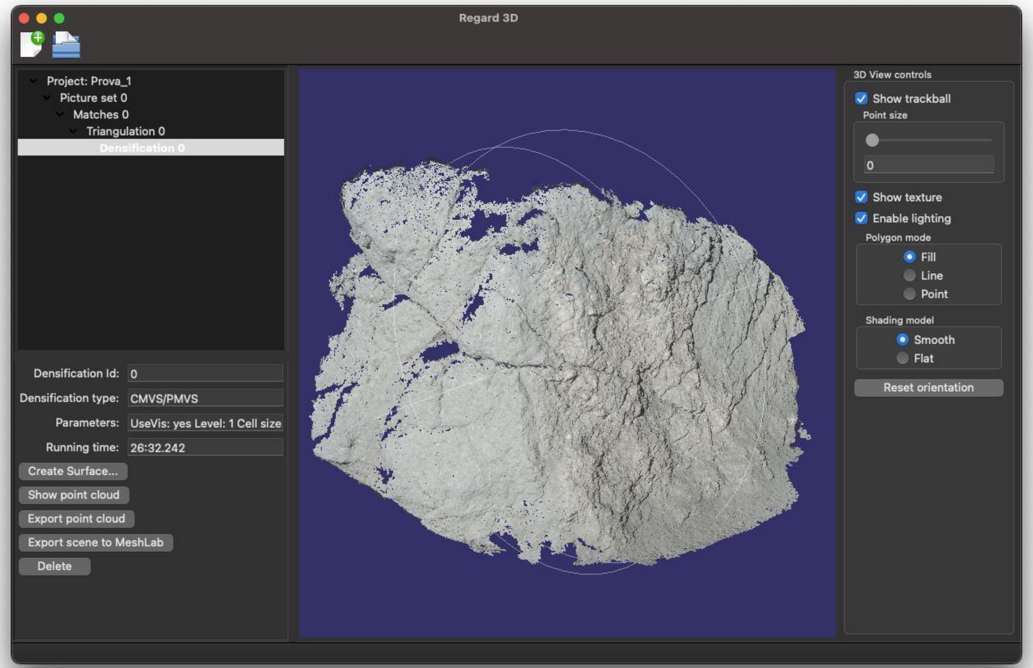


Figure 18: Example of a dense point cloud generated by Regard3D using photographs of a boulder from Apollo 17 astronauts during EVA activity.

Metashape

Metashape from Agisoft, formerly named Photoscan, is a photogrammetry commercial software capable of image matching, disparity map production, sparse and dense point cloud generation, meshing, texturing, DEM and orthoimage generation (only Pro account version).

We are listing this commercial software as it is user friendly and largely used, considered one of the industry standards and the standard single licence is cost affordable. The Pro version, apart from DEM and orthoimage generation, has more advanced tools for point cloud processing and it features also remote execution capabilities based on cloud-services. This makes it possible to use the desktop application itself for submitting jobs, downloading, and visualizing the resulting models. Browser visualization to review the products is also available on any device, but no processing commands can be submitted via browser to the cloud service, all needs to be done on the application on the local machine.

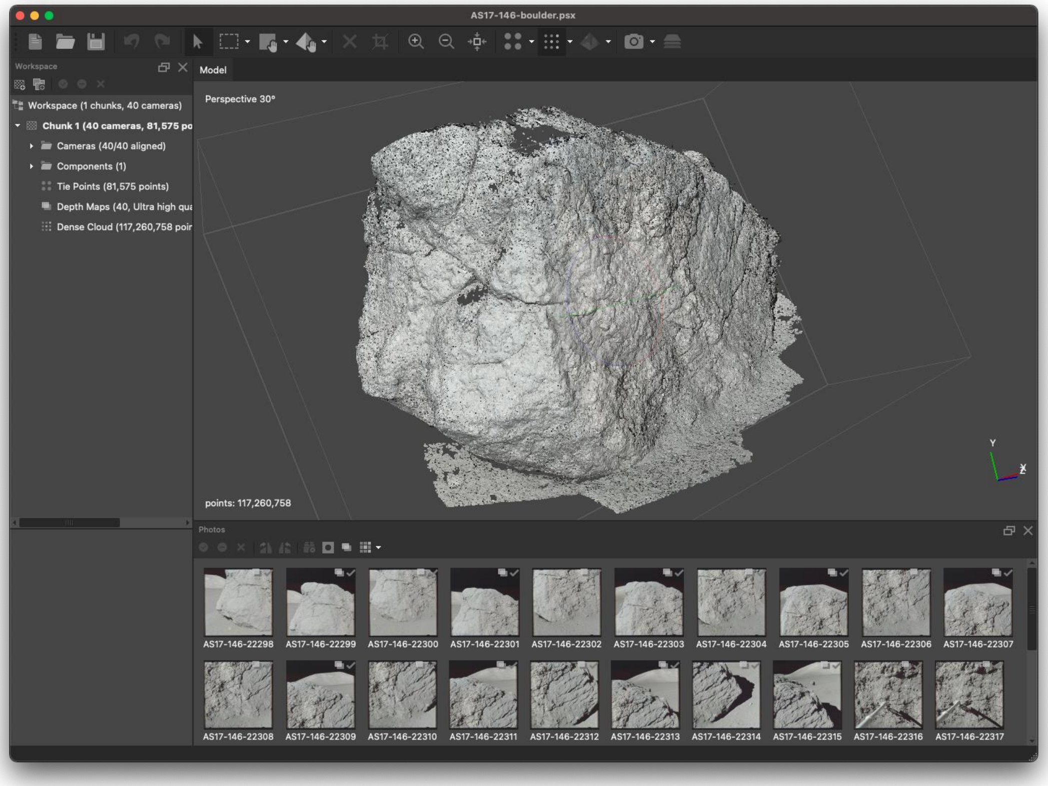


Figure 19: Example of the main Metashape interface with a dense cloud model generated from masked scanned photographs from Apollo 17 astronauts' EVA. On the left panel all the products from its pipeline are selectable, on the bottom all the images used for DOM production are visible, along with their masks.

Web services

MarsSI

MarsSI (Quantin-Nataf et al., 2018) is a web-based platform that enables the processing of different images from different sources on Mars. It integrates a web-gis and allows to locate stereo pairs from different instruments and perform all the processing in ASP on the server side. On the server backend MarsSI uses ISIS and ASP and is able to automatically download from PDS the required images, pre-process them through ISIS and create DEMs with ASP.
It is almost unsupervised as processing steps are submitted to the server by a button click. Once the process is done it is possible to copy all the obtained products into the user space on the server and access them through an ftp application.
Although there is little or no control on the fine tune of parameters used by every single ASP routine, it generally produces good quality results, and it is ideal for large datasets.

The main service page can be found at:
https://marssi.univ-lyon1.fr/MarsSI/

The “getting started” button inside the personal space provides a step-by-step guide through all the possibilities of this service.

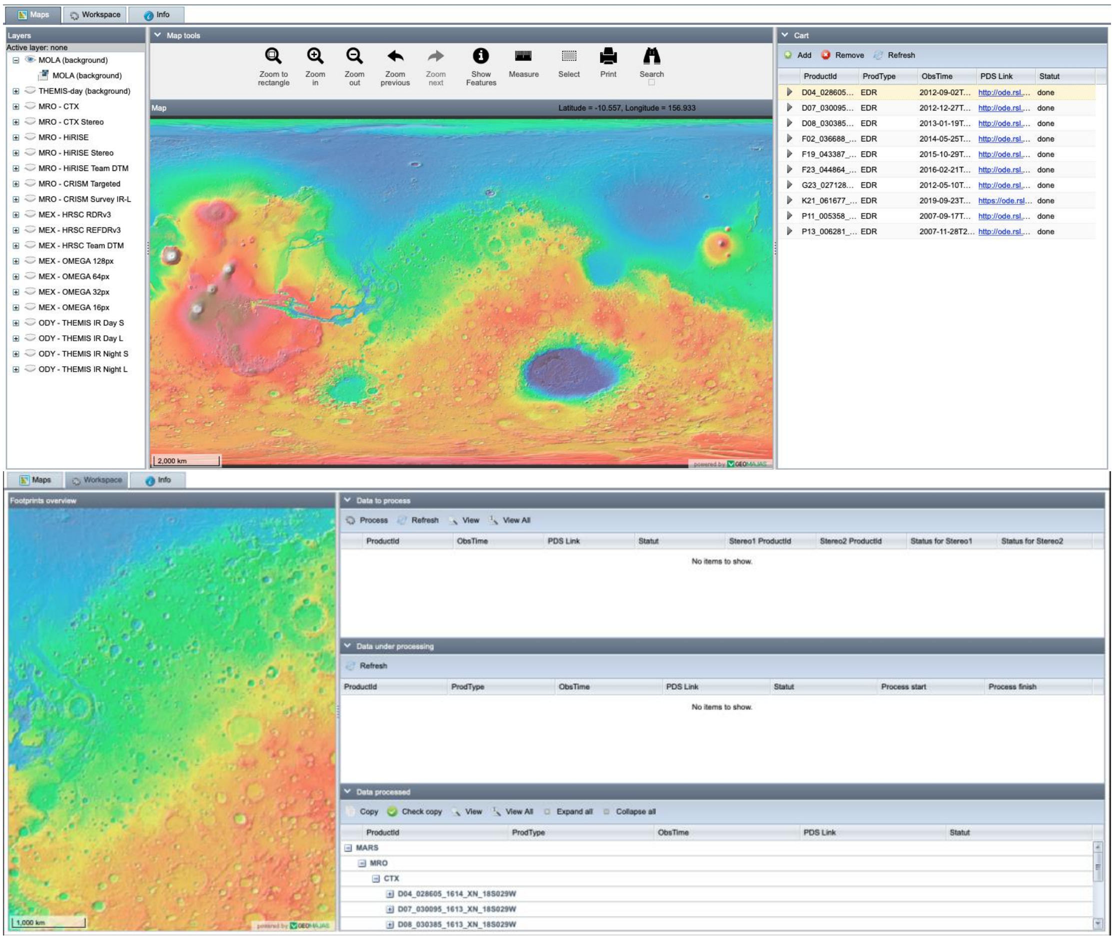
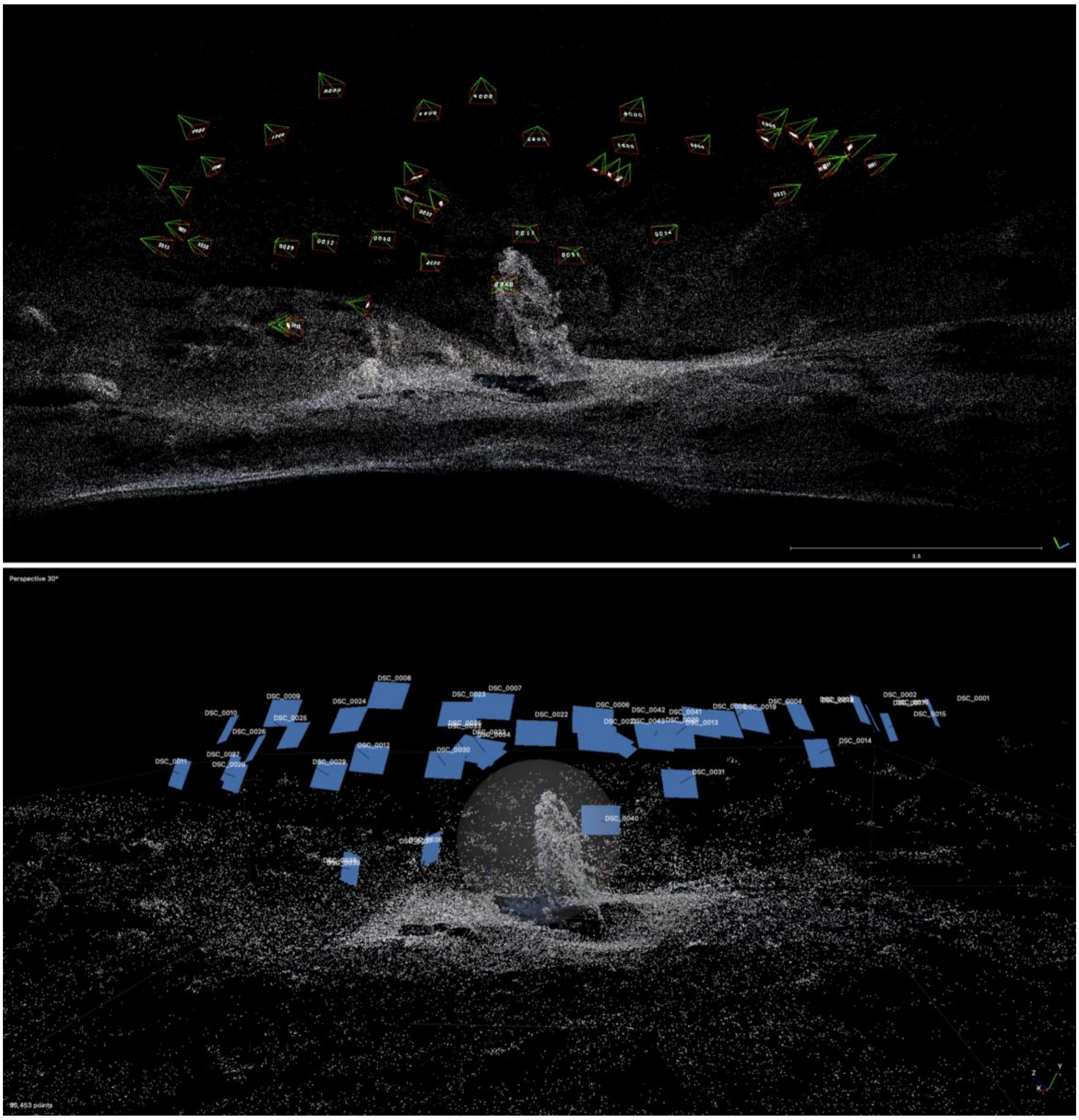


Figure 20: The main interface of MarsSI. On the left panel the instruments that can be handled by the service, and in particular the production of CTX stereo and HiRISE stereo DTMs. Other products can be downloaded as well. In the bottom panel it is visible the “workspace” tab, where after the image pairs selection on the main panel it is possible so submit jobs through the “process” button, to check the data under processing, and to review the processed data and copy them into the ftp space associated to the user account.

Examples of DOMs from open source and commercial software:

In this section it is illustrated a SfM reconstruction obtained by different open source and commercial software packages. Although each of them has its strengths and drawbacks, overall, the results are comparable.



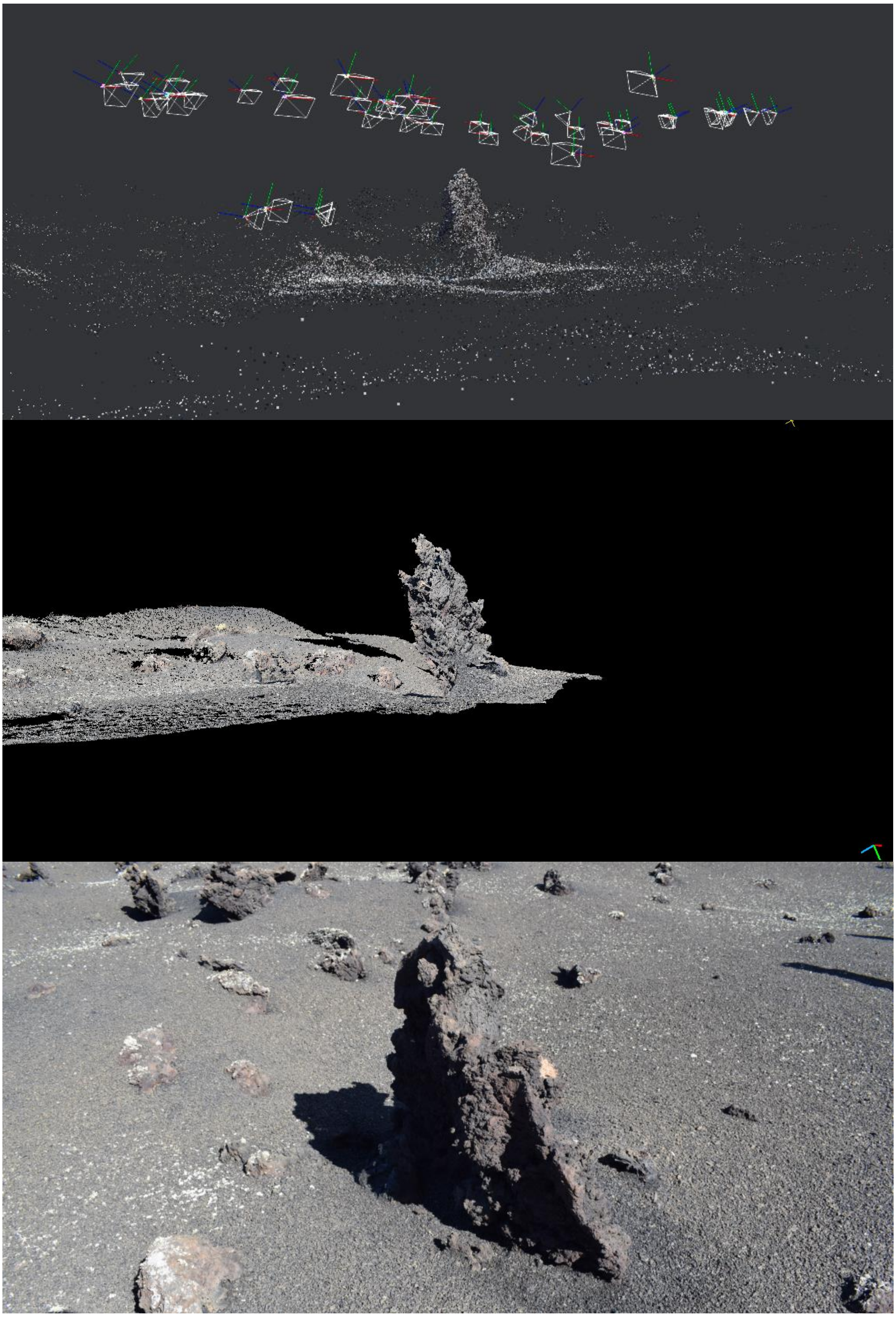


Figure 21: examples of the same DOM from a reflex camera in a planetary analogue environment. a) MicMac and b) Metashape c) Meshroom d) Regard3D. In e) the real outcrop of basaltic rocks on a lapilli field.

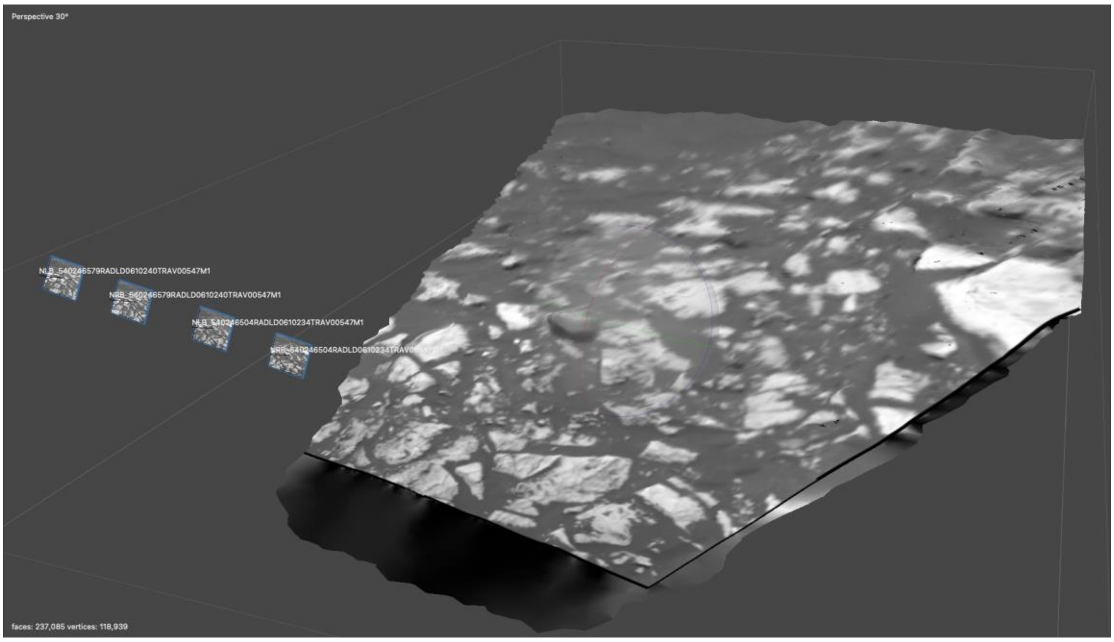


Figure 22: example of NAVCAM stereo images from Curiosity rover. Model created in Metashape. Cameras with thumbnails of the actual frame are visible on the left side. More models on stereo NAVCAMS from Mars Exploration Rovers can be generated through ASP (as shown in this guide https://stereopipeline.readthedocs.io/en/latest/examples.html#mars-exploration-rovers)

Other projects:

Structure from motion

OpenSFM
https://www.opensfm.org

VisualSFM
http://ccwu.me/vsfm/

OpenDroneMap
https://www.opendronemap.org/webodm/

Visualization

Blender photogrammetry importer
https://github.com/SBCV/Blender-Addon-Photogrammetry-Importer

Meshlab
https://www.meshlab.net

CloudCompare
http://www.cloudcompare.org

LIME
https://virtualoutcrop.com/lime

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