

PREPARING 3D VISION AND VISUALIZATION FOR EXOMARS

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ABSTRACT

PRoViP (Planetary Robotics Vision Processing) and PRo3D (Planetary Robotics 3D Viewer) are the main ExoMars 3D vision ground processing and visualization elements for camera instruments' data. PRoViP uses PanCam stereo and/or other ExoMars imaging instruments to generate 3D data products. PRo3D is a powerful real-time rendering and 3D data analysis tool for 3D annotation, target definition, quantitative analysis and geology. We report on the capabilities and development status of the tools tailored to the ExoMars case and their embedding in the ROCC (Rover Operations Control Centre) context as designed for tactical and strategic mission support. The PRoViP processing workflow is summarized, and PRo3D main features for real-time visualization and analysis of huge surface 3D data sets are described. By means of the image & 3D data products' data provision & analysis process for the ExoMars design simulations in autumn 2021, we demonstrate some of the main use cases as expected for ExoMars after its landing. Prospects for related exploration missions (e.g. Mars 2020 and HERA) are pointed out.

1. EXOMARS SCOPE

The ExoMars 2020 mission, currently under re-schedule, will provide a heterogeneous set of data from different instruments captured on the surface of Mars [1]. Imagery for science target selection, navigation, or close-up detailed visual analysis for geology and georeferenced sensor data such as from the WISDOM ground penetrating radar instrument [2] will be complemented by multi-spectral imagery from orbiters. ExoMars will contain a drill designed to acquire a core sample from a maximum depth of 2 meters. In this context, 3D vision processing and visualization is an essential component to pertain 3D information about the Martian surface in various scales, allow spatial analysis for geology [3] and aeolian features [4], will feed tactical and strategic planning with morphology and scale, and keep situational awareness of Rover and science teams on an immersive level. PRoViP and PRo3D provide a 3D vision processing

and visualization cadence (Figure 1), using the dedicated data scheme of "Ordered Point Clouds" (OPC) [5].

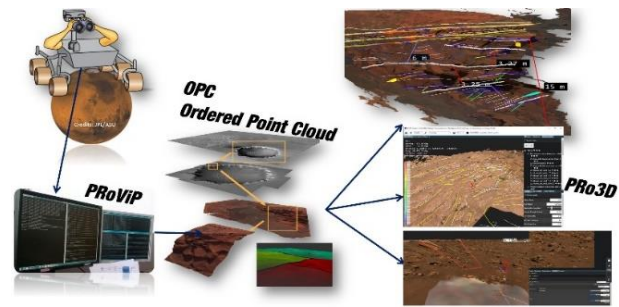


Figure 1: Interplay of PRoViP processing with PRo3D visualization, using OPC (Ordered Point Cloud) data structure for efficient exchange.

2. PROVIP 3D VISION PROCESSING

Stereoscopy on PanCam [6], NavCam, LocCam and combinations thereof (and with CLUPI [7]) enables the generation of 3D vision products (e.g. Digital Terrain Models (DTMs), textured meshes, panoramas and derived products) for a subsequent visualization. Stereo photogrammetry performs individual processing steps using the instrument's geometric parameters and known pointing angles of the pan-tilt unit (PTU) as follows:

- Stereo matching for dense correspondences
- 3D triangulation to project onto an infinite virtual cylindrical or spherical gridded model
- Projection of image texture onto the grid
- Data fusion between adjacent stereo patches
- Production of an OPC (Ordered Point Cloud).
- For the 2D mosaic case: Projection of camera textures and mosaicking with optimization to minimize visual effects between patches.

To realize this workflow, PRoViP consists of a set of "processors" that are executed by the ROCC *Automated Data Processing* (ADP) Pipeline. Their cadence (Figure 2) depends on the interfaces provided, specified in the ExoMars ROCC-to-PanCam Interface Control Document ICD [8].

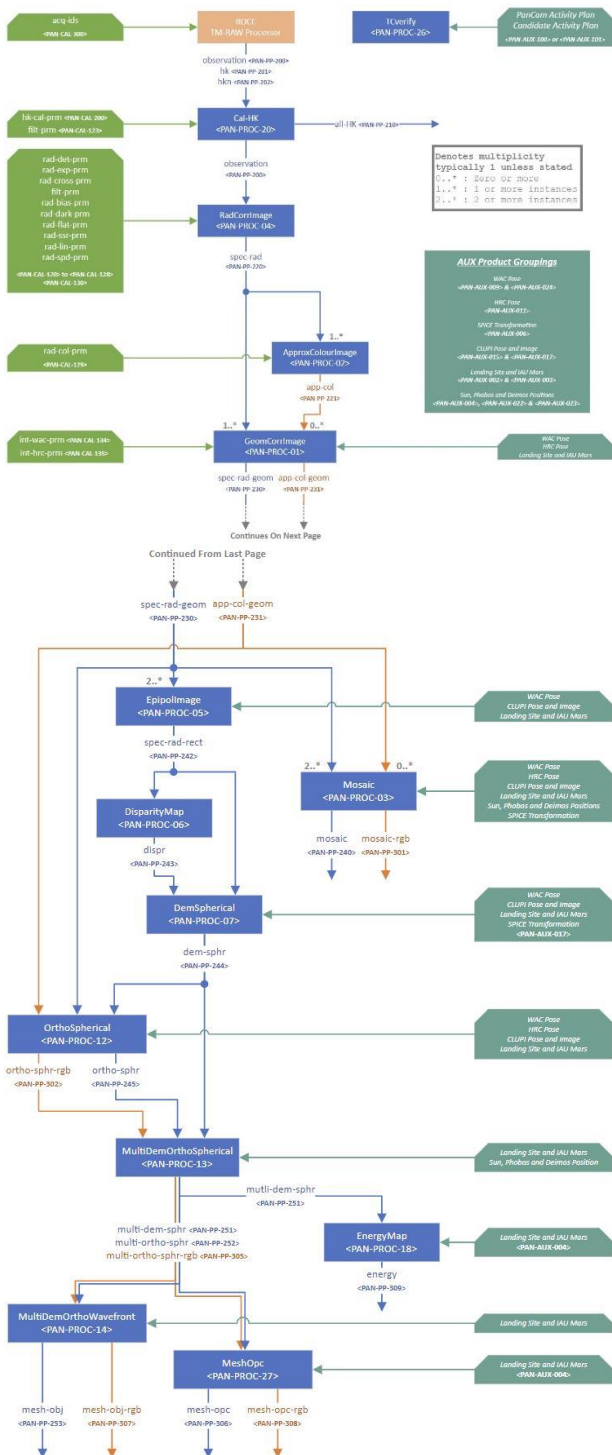


Figure 2: PanCam ROCC Pipeline, tactical branch. The following is a list of the processors of the tactical branch, as depicted in Figure 2:

- GeomCorrImage* corrects radial lens and adds camera poses to the meta data
- Mosaic* takes image tiles and creates a two-dimensional image panorama

EpiPollImage performs epipolar rectification of input stereo image pairs

DisparityMap uses stereo matching to compute the column-wise and row-wise disparity maps for rectified input stereo image pairs

DemSpherical performs ray forward intersections to compute spherical depth maps (including xyz maps containing Cartesian coordinates for each pixel) from the input disparity maps

OrthoSpherical projects the provided input texture images onto the corresponding depth maps

MultiDemOrthoSpherical stitches together multiple spherical single-stereo depth maps and ortho images to a large combined mosaic

DemCartesian performs ray forward intersections to compute Cartesian depth maps from the input disparity maps

OrthoCartesian projects the provided input texture images onto the corresponding Cartesian DEM

MultiDemOrthoCartesian stitches together multiple Cartesian single-stereo depth maps and ortho images to a large combined mosaic

MultiDemOrthoWavefront converts a spherical or Cartesian DEM mosaic to a three-dimensional Wavefront model, in particular for interfacing with the ExoMars tactical planning tools [9]

MeshOPC converts a spherical or Cartesian DEM mosaic to an OPC to be used by the PRO3D viewer application

RoughnessMap computes a roughness map from a Cartesian depth map

SlopeMap computes a slope map of a Cartesian depth map

HazardMap computes a hazard map from a Cartesian depth map

EnergyMap computes a solar energy map from a spherical depth map.

Early in 2022, major parts of PROViP were successfully installed in the operational environment of the ROCC at ALTEC in Turin / Italy. It will undergo some functional upgrades still in preparation for the mission.

3. PRO3D VISUALIZATION

The Planetary Robotics 3D Viewer, in short PRO3D, is an interactive 3D visualization tool to allow members of the Science and Operations teams to work with high-resolution 3D reconstructions of the Martian surface [3].

As outlined in Section 2, 3D reconstructions stem from a variety of camera instruments capturing images either from orbit or from ground-level. The key requirement is to view and analyze these data together in their common

geospatial context. PRoViP performs the necessary transformations while PRo3D allows users to browse 3D surface reconstructions ranging from kilometer to micrometer scale. This requirement raises two challenges: **First, (1)** representations of different resolution exist for the same region on Mars, and **second (2)**, combining large scale orbiter DTMs and multiple high-resolution rover reconstructions can easily lead to gigabytes of geometric and image data.

3.1 Priority Rendering

We address (1) by employing *priority rendering*, a technique that lets users determine the sequence of surfaces in which they are rendered by assigning a number to them. Surfaces with higher numbers are rendered on top of lower-number surfaces by by-passing the depth test.

Naturally, this method leads to occlusion artefacts, but we have found that the priority assignment is more straightforward, and the outcome is more comprehensible for users when compared to using polygonal offsets. Further, users are able to assign the priorities at the visualization stage, which allows them to adapt the rendering of their scene interactively over their current need. This is an advantage to data-fusion approaches, e.g., cutting out and stitching meshes of different resolutions, typically applied at the pre-processing stage. These are difficult to parametrize without the immediate visual feedback and lead to inflexible scene configurations.

3.2 Out-of-Core and Level-of-Detail Strategies

When dealing with (2), large data in a 3D visualization setting may face two hardware bottlenecks, first, the 3D data (i.e., 3D geometry and image textures) to be surveyed exceed the size of the main memory and second, the 3D data currently in view exceed the resources of the graphics card in terms of frame time and graphics card memory.

We address these typical bottlenecks with an out-of-core loading strategy and a level-of-detail rendering scheme both utilizing the tile and hierarchical nature of the OPC data structure [10]. When users decide to import a surface reconstruction, consisting of one or more OPCs, initially only the coarsest detail in geometry and imagery is loaded from disc into the main memory. This enables PRo3D to hold a large number of surfaces and their metadata with a relatively small footprint in memory.

With an OPC in memory, the level-of-detail decision module traverses the data structure and evaluates whether a patch is sufficient for the current view. If that is the case, we render it, i.e., send it to the graphics card, and if not, we need to traverse the data structure further investigating its four sub-patches which provide higher detail.

To decide if a patch is sufficient, we chose a screen-space metric, which determines the ratio between texture pixels,

i.e., texels, and screen pixels. The highest detail a screen can visualize is when the ratio between texels and pixels is 1:1. This intuitive metric makes it easier for users to adapt the metric to accommodate for less capable hardware, for instance by changing the ratio to 1:2 effectively letting a texel cover a 2x2 pixel square instead of a 1x1 single pixel. In summary, our approach shows the Martian surface in high detail in the foreground and in lower detail in the background without a noticeable decrease of visual quality while efficiently using hardware resources.

3.3 Geological Annotation and Analysis

PRo3D's initial use case was to support planetary geologists with tools to conduct remote geological analysis on 3D digital outcrop models, i.e. 3D surface reconstructions mostly from science cameras. However, the suite of measurement tools can also be employed to serve operations use cases, e.g. judging distance and height of terrain to be traversed. All measurements are based on the interaction of the user clicking on a screen pixel which spawns a 3D ray being intersected with the surface geometry of the highest available detail consisting of millions of triangles. To reduce computational load, we sort the triangles into a kd-Tree, a spatial acceleration data structure allowing to exclude many triangles from being tested for intersection.

The resulting points on the surface can form a single point, line, polyline, or polygon annotation. We compute a series of measurements for each annotation, such as length or bearing and allow users to add arbitrary text displayed as 3D billboards facing the screen. To convey semantic information annotations can be styled by color and thickness. PRo3D currently offers two tools specifically designed for conducting remote geological analysis. The first, dip-and-strike is essential for judging orientations of strata and cross-beddings. The users pick points on the surface forming a polyline, while on completion we use a PCA based method (as suggested by [11]) to fit a plane to the respective positions. The second is the vertical thickness tool where users connect two points with a line and further manually specify dip angle and dip azimuth. This lets geologists estimate the true vertical thickness of strata as opposed to their apparent thickness. As in-depth geological interpretations may contain thousands of annotations, PRo3D offers a Graphical User Interface (GUI) to sort annotations hierarchically into named groups. To carry over measurements taken in PRo3D to other tools it offers a variety of export methods, such as CSV or GeoJSON.

3.4 Viewplanner

The Viewplanner (see Figure 3) is an integrated tool to optimize capturing positions for a rover camera instrument and to perform visibility analyses [12].

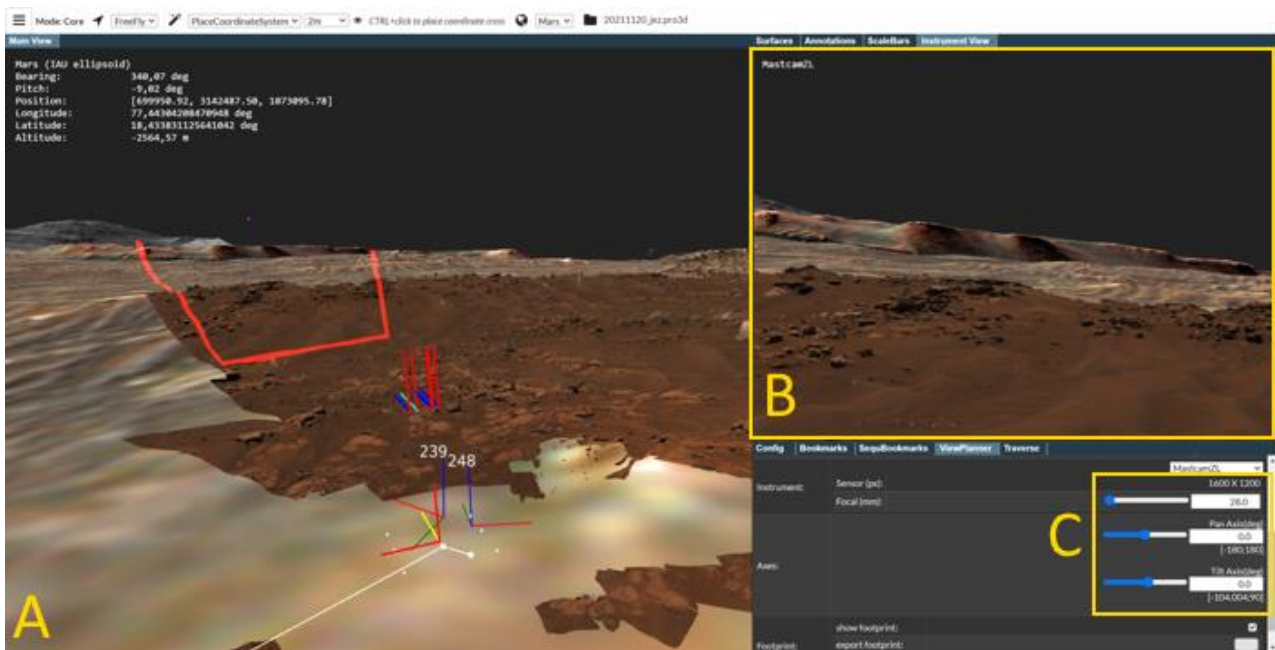


Figure 3: Simulating the left Mastcam-Z of the Perseverance Rover. The camera instrument parameters are adjusted in the GUI panel (bottom right), the corresponding instrument footprint is shown in the 3D view (left) as red polygon together with an abstract rover model, the simulated view is rendered into the upper right frame. © NASA JPL/CalTech/ASU/JR/VRVis; HiRISE data: USGS (DTM & panchromatic Ortho layer) and JPL Mars 2020 Science Team (RGB Ortho layer).

View planning starts by placing the rover onto a desired surface position. For that, already available DTMs are used, which are mainly obtained from orbiter imagery but can also include previous reconstructions from rover imagery. The rover and its instruments are represented in an abstract way by dots and lines. Next, the operator chooses a camera instrument in the GUI and adjusts its parameters such as the PTU angles. A red polygon encloses the area of the planetary surface (“footprint”) covered by the chosen instrument and settings. A simulated view of the camera instrument is shown in a separate frame. Both the polygon of the visible region and the simulated view are updated in real-time when the operator changes the instrument settings. This highly interactive and geospatially accurate approach allows to efficiently find optimal viewpoints and camera settings.

An extension of the Viewplanner supports capturing of panoramas. For that, a planetary scientist first marks a region of interest on the surface and then positions the rover and chooses an instrument. Instead of adjusting instrument parameters, one defines the percentage of overlaps between adjacent images. This is done for the horizontal and vertical overlap. The Viewplanner then calculates the pan and tilt settings for each single image. The view frustum of every shot is visualized and together

they show how good the region of interest is covered. Users can step through the set of single shots (PTU settings) and study simulated views. It is easy to change the camera instrument and compare for example the number of single shots needed to obtain the desired panorama. Stereo cameras are also supported in this extension, which is a preliminary research result and not yet integrated into official PRo3D releases¹.

3.5 Storytelling

Users can fly to all objects of a PRo3D scene. Besides that, navigation is further supported by stored viewpoints (bookmarks). Scientists can smoothly move between different interesting locations without losing the overall geospatial context. Furthermore, they can define a camera path through the scene by arranging bookmarks into a sequence like a storyboard. This is a first step towards storytelling. For presentations, a video can then be produced through batch rendering².

3.6 Traverse

A rover traverse can be loaded into PRo3D and is shown as polyline connecting its single waypoints. NASA provides the data as GeoJSON file. The traverse can be

¹ See a demo video on youtu.be/CMLgEZkGLTQ

² <https://www.youtube.com/watch?v=67KnMVZoxuU>

used for navigation to fly to a chosen waypoint, which are also listed in the GUI. Furthermore, users can create a view plan for a selected waypoint. The rover is then automatically placed there, and operators or planetary scientists can immediately start to optimize capturing for a chosen instrument from that position.

4. USING PROVIP AND PRO3D IN EXOMARS SIMULATIONS

Four training sessions to practice decision making by the strategic ExoMars Science Team were initiated and conducted in 2021. Each payload instrument team nominated members for a team of Simulation Officers. They then created scenarios the rover team would encounter after landing at Oxia Planum on Mars with simulated instrument data. Simulated PanCam and NavCam data were selected from previous field campaigns and past and ongoing Mars rover missions and then processed by PRoViP. PRo3D scenes were created for each sol to visualize the OPC data in a Rover Navigation Frame and to represent the viewing angles and distances required. Scale bars were placed around the outcrop, and the locations of data collected from the other instruments such as PanCam HRC and ISEM (Infrared Spectrometer for ExoMars) were mapped to provide spatial context for decision making. The geology was interpreted using the input images with the 3D data and mapped onto the OPCs. The dip and strike of key boundaries and internal layers was calculated [3]. This data together with measurements of key distances, feature dimensions and viewpoint orientations were used to aid selection of targets for the proceeding Sol's activities and test / train geologic annotations and findings.

Each simulation required the team to go through the meeting and decision structure of a particular sol (a sol is a day on Mars, counted from the day of landing) of the mission. The day before the simulation included a briefing, and the day after a debriefing session. Data were released in packages starting several days before the simulation, as they would be received in a real mission.

The first simulation (Sim#1) was themed 'After Landing'. It simulated sol #4 during the Post Landing to Egress (PLTE) phase. At that point, the rover would be situated on its landing platform and in the middle of acquiring a 360° PanCam panorama while being readied for egress. NavCam and available PanCam frames allow for hazard identification, a first geological interpretation of the scene, and enable prioritised targeting for high-resolution images with HRC (High Resolution Camera). A 360° panorama had been obtained from a platform with a PanCam emulator during the 2019 ExoFit trials in Chile [13], and simulated images were cut out from that panorama and provided with scale bars and angles added using PRoViP. Sims#2 was a 'Site Survey'. In this scenario simulating planning for Sol 51 of the mission, a layered outcrop (imaged on Sol 48) was approached and assessed as a

potential drill site. For this scenario, a mosaic of layered sedimentary rocks [7], [14] obtained with Mars Exploration Rover (MER) Spirit's Pancam [15] and supported with a 360 Navcam panorama was provided. PRo3D was used to provide simulated PanCam WAC (Wide Angle Camera) and HRC images of the scene from different distances. The stratigraphy was interpreted from images and OPCs in PRo3D and the thickness and orientation of the outcrop layers was measured to characterise the outcrop geometry and locate a potential drill site (Figure 5). The field of view of additional imaging and spectral targets were mapped onto the datasets. The outcrop, named "Teuton" was sub-divided into three lithologically distinct units which were analysed in detail from the simulation WAC and NavCam data collected on Sol 49 Figure 6. The lowermost "Byzantine" unit was 3 – 5 cm thick and characterised by sub-planar thin beds and laminations and a rough surface texture. The 8 to 10 cm thick "Cuman" unit was characterised by thicker sub-planar beds and a smoother surface texture. The topmost unit – "Tatar" was 85-119 cm thick and interpreted to consist of cross-laminated smooth textured material. In Sim#3 – 'Opportunistic Science Trade-Off' – the rover remained at the same site but an alternative potential drill site was offered, which exhibited mineral veins (Figure 4). The original images had been acquired with Mars Science Laboratory (MSL) Curiosity's Mastcam [10] in Gale crater on Mars. PRoViP and PRo3D were used to create simulated PanCam HRC images at different angles and distances of that scene. However, the science team decided during that simulation of Sol 52 planning to stay at their current location and start drilling. The analysis of the acquired drill samples with the instruments in the rover's internal Analytical Laboratory Drawer (ALD) were simulated for two sols during Sim#4, 'ALD Analysis'. Simulated retakes of HRC images at different camera pointing angles were provided for this scenario.

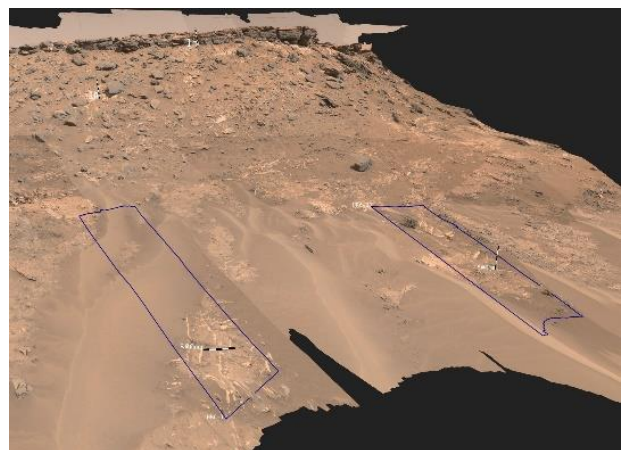


Figure 4: Sim#3 data set (from MSL Mastcam Sol 1272) processed by PRoViP & visualized in PRo3D to gain a simulated PanCam view, with next Sol's HRC footprints. Credits: NASA/JPL-Caltech/MSSS/ASU

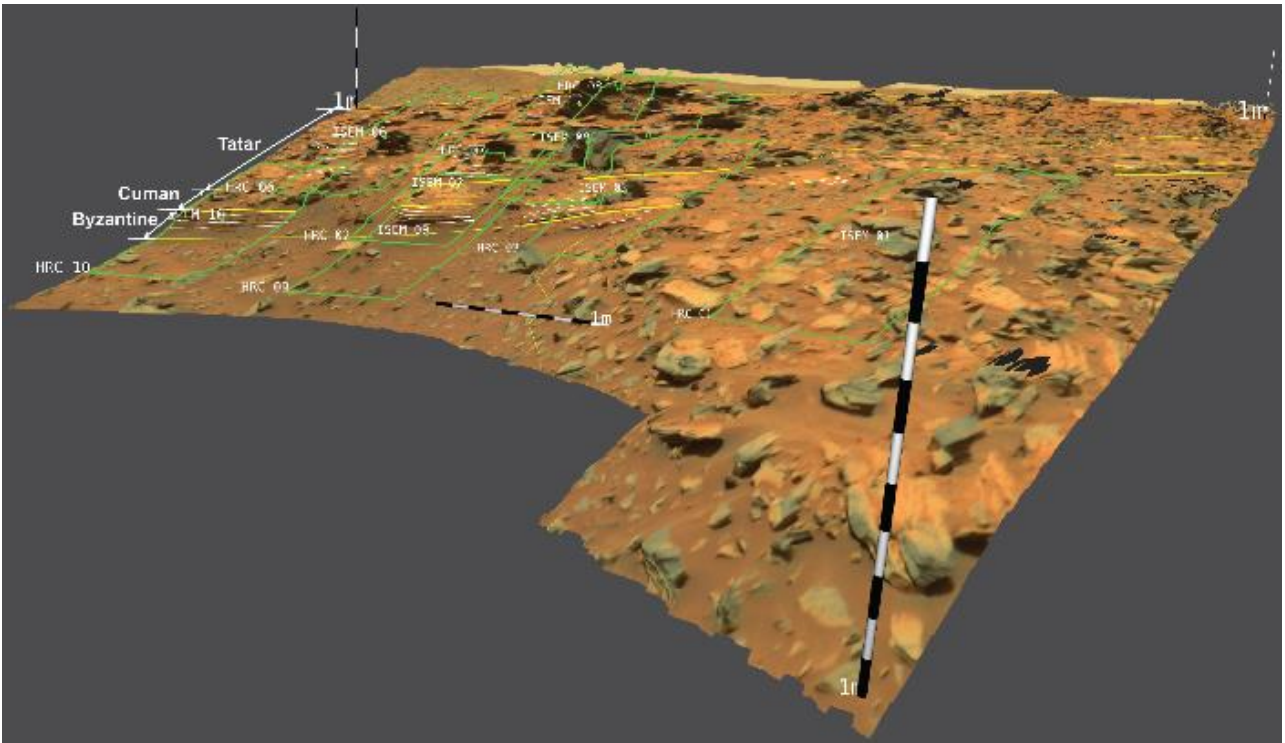


Figure 5: Geologic annotation/interpretation of MER-A Sol 746 (Gibson Formation) Pancam PRoViP stereo-to-OPC processing result. This was used as data collected during Sol 48 of Sim#2, named the Teuton Outcrop. The three key lithological units identified – Byzantine, Cuman and Tatar – and the locations of HRC (green quadrilaterals) and ISEM targets (green points) requested are labelled. Credits: NASA/JPL-Caltech/MSSS/ASU



Figure 6: Geologic annotation/interpretation of MER-A Sol 748-751 (Gibson Formation) Pancam PRoViP stereo-to-OPC processing result. This was used as data collected during Sol 49 of Sim#2, and was used to measure the true thickness of the units (thick white lines), and the dip and strike of the key boundaries and internal layers (disks and arrows coloured by dip magnitude, the red lines represent the strike direction). Credits: NASA/JPL-Caltech/MSSS/ASU

5. OUTLOOK

During and after the main Rover mission, the PPro software suite³ will be the primary tool for analysis of landforms, bedforms and physical geological structures as seen in PanCam and other imaging data. The 3D vision data processing and visualization software elements will be used for both operations and science analysis. The inclusion of scale bars and Rover models in generated scenes will allow the human-scale of outcrops of landforms to be easily intuited by users – a challenge when using non-3D Rover images. The virtual working areas generated by PProViP and visualised in PPro3D will both allow scientists and engineers to work as if they were in the field, and to rapidly make measurements that would be difficult or time-consuming in a physical environment.

In future simulations, the hand-over between strategic and tactical shifts will be practised. The Pro software will be vital for a quick-turnaround of data to allow targeted remote sensing. In the upcoming ExoMars Rover mission, PPro software will be used both for operational decision making and for scientific analyses.

For example, a key aspect that sets the ExoMars Rover apart from other Mars surface missions is its deep drill capability. This allows the mission to sample from as deep below the surface as 2 m, a depth at which even ancient astrobiological biomarkers [1],[16] would have been preserved from the martian surface radiation environment. The PPro tools will be particularly useful for assessing the surface outcrop expression of 3D geological structures that continue into the subsurface, including layers, fractures and mineral veins. The PPro suite allows surface measurements to be made accurately, and then extrapolated into the sub-surface where they can be combined with underground remote sensing data such as those from the WISDOM ground penetrating RADAR. This multi-instrument 3D data fusion should allow the mission operators to position the rover in the correct place on the surface to ensure that the perfect geological material is sampled, and from the deepest possible depth..

For science, the PPro tools allow large numbers of reliable measurements of the orientation and size of geological structures to be made. Such a capability will provide mission geoscientists with the knowledge required to test hypotheses about the origins of the rocks being explored, and to make more informed inferences about specifics of the palaeoenvironments under which the rocks were laid down. For example, by measuring the steepness and orientation (dip and strike) of layers and thin laminations in bedded sandstones, the formative transport direction and original surface angles can be calculated. Given that the ExoMars landing site appears to be made up of sedimentary materials [17], which might have been laid

down by wind or water, this information will be important during the ExoMars Rover mission for determining the geological history of the region.

Beside the ExoMars application deployment, PProViP and PPro3D are already in heavy use for 3D vision for Mars 2020 Mastcam-Z 3D Vision [18], and their application for the HERA mission is in development, with extension of the processing, data representation and fusion capabilities to small bodies and an emphasis on provenance on the data presentation side.

Various additional functions for PProViP are currently in late implementation stage such as long baseline stereo, interfaces to spectral analysis tools, 3D data registration assets, or localization support functions.

The Viewplanner of PPro3D is currently extended to support optimization of long baseline stereo positions. Other additional features of PPro3D include 3D Geographical Information System (GIS) functionality and collaboration support by embedded storytelling mechanism and Notebook-style interfaces.

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³ PProViP and PPro3D, extended by a 2D viewing tool called PProPano

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