POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

Master of Science in Aerospace Engineering

Master Thesis

Preparation, simulation and testing of remote Rover operations for a Martian robotic mission

That’s one small step for ExoTeR

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Oh, I'll tell you where to begin: three negro women chasing a white police officer down a highway in Hampton, Virginia in 1961. Ladies, that there is a God-ordained miracle!

Hidden Figures

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Summary

The 2020 mission of the ExoMars program is meant to deliver a European Rover and a Russian Surface Platform to the surface of Mars. The ExoMars Rover will travel across the Martian surface to search for signs of life. It will collect samples with a drill and analyse them with a dedicate suite of scientific instruments. ExoMars will be the first mission to combine the capability to move across the surface and to study Mars at depth.

Within this framework, Altec has the responsibility to design, build and validate the Rover Operations Control Centre (ROCC) for the ExoMars 2020 Rover.
The ROCC will host a team of engineers and scientists who will support the assessment on the data received from Mars and plan next-SOL Rover activities accordingly.
A dedicated facility of the ROCC, the MTS (Mars Terrain Simulator), will be used to rehearse, simulate and validate the Rover activities during the operations definition phase, and Ground operator training. It will eventually support all the activities and contingencies which can arise during the surface mission.

This thesis reports on an industry-based internship, which has been dedicated to support the Altec ExoMars Team in the definition, preparation, and execution of test campaigns of validation and simulation for Ground operations.

ExoTeR is a robotic platform, whose dimensions are half scaled with respect to the real ExoMars Rover. It has been used for test preparation and execution in the MTS, with a mock-up of the landing platform.

The 3DROCS Ground SW has been used to carry out the data assessment, perform the necessary planning activities and provide ExoTeR with the complete set of commands during the simulation campaign.

Contents

List of Figures

List of Tables

List of Activity Plans

Chapter 1

ExoMars mission

The ExoMars Programme aims at demonstrating technologies and operative sequences for future exploration missions, as well as contributing to important scientific pursuit.

The programme consists of two missions to Mars under ESA leadership exploiting, respectively, the 2016 and 2020 launch windows.
In the 2016 mission the Mars TGO (Trace Gas Orbiter) satellite was successfully set in a Martian orbit to examine the existence of Methane sources on Mars and to study the Martian atmosphere. In the same mission ESA lost the EDL (Entry, Descend and Landing) Demonstrator which would have performed in-situ surface analyses.
The 2020 mission involve the ESA Rover and the Russian Landing Platform. When the 300 kg Rover will successfully Egress the surface module, after a soft landing at the selected landing site, the Surface Mission will begin. The ExoMars 2020 Rover mission will mainly use the 2016 TGO as a relay satellite to transfer data between the Ground and the Rover Module. Figure 1.1 depicts the ExoMars modules after the RM Egress.

1.1 ExoMars 2020 mission description

The 2020 Rover mission will allow for surface mobility, guaranteeing a maximum distance of 100 m per day, and the possibility to collect subsurface samples. The Rover will collect, prepare and distribute samples to a suite of scientific instruments accomodated on board.

The Rover Surface Mission (RSM) developed by ESA aims at discovering signs of past and present life on Mars and investigating the geochemical environment throughout the subsurface depth (see reference [15]). In this mission it is possible to understand the habitability of Mars and identify several risks in case of a probable human mission.

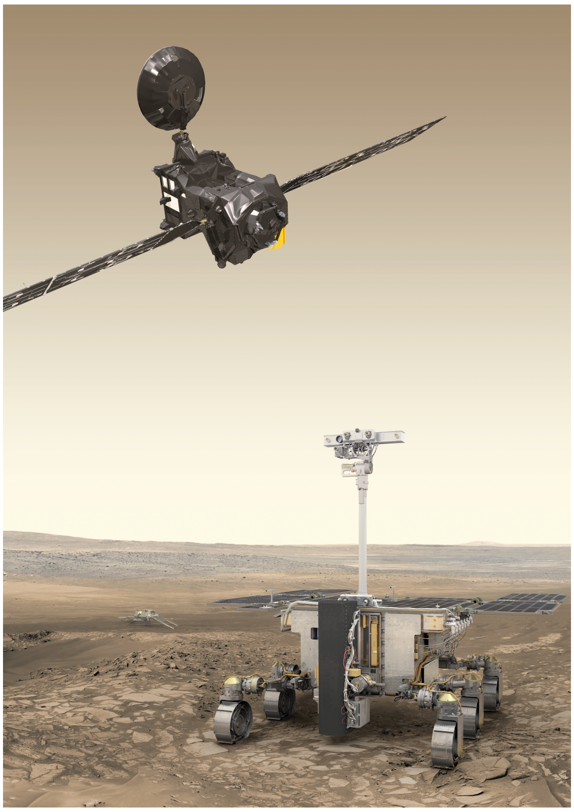


Figure 1.1: ExoMars 2020 Rover in foreground, the Surface Platform in background and the Trace Gas Orbiter on top (Credit: ESA/ATG medialab, EXOMARS ORBITER AND ROVER, March 27, 2017. From https://m.esa.int/spaceinimages).

1.1.1 ExoMars system definition

The 2020 ExoMars mission launch will be carried out by the Russian three-stage Proton vehicle and the Breeze-M upper stage.

The Space segment is composed of the Carrier Module (CM) and the Descend Module (DM). The latter includes the Russian Landing Platform (LP) with its payloads, as well as the ESA Rover Module (RM) with the Pasteur Payloads suite (7 European and 2 Russian instruments).

The Ground segment is composed of European and Russian teams. Each team is responsible for given space components through different mission phases. The ROCC in Turin will be the ExoMars Rover Operations Control Centre, and will hold operational responsibility during the RSM phase. The ROCC will also host the Science Operation Centre (SOC), which will have the command and control of payloads mounted on the Rover. The ESOC/MOC (European Space Operations Centre/Mission Operation Centre) in Germany will host the TGO Data Relay Operations Centre and will manage the communication between the Rover and the ROCC, as well as between ROCC and SPOCC (the Surface Platform Operations Control Centre in Russia). ESOC will also be the responsible of the Spacecraft Composite (CM + DM) Control during the cruise. The ESAC in Spain will manage the long-term archive of the Pasteur Payload Science Data and their dissemination. The mission will benefit from the utilization of the ESTRACK Communication Subnet ESA ground stations and the Deep Space Antennas Russian Ground Stations.

1.1.2 Mission summary

The Rover Module, accommodated within a Descend Module, will be launched in July 2020 to a Mars transfer trajectory, and will land on the Mars soil approximately eight months later.

During the interplanetary cruise three check-out will be performed, retrieving a telemetry update from the RM lodged in the Russian LP, within the CM. In this phase the RV is linked to the DM through the umbilical, transferring data and providing power.

Once arrived in Martian atmosphere, the DM separates from the CM, its deceleration begins and the DM Coast phase starts. A controlled descent is assisted by heat shield and parachutes up to touchdown. The CM is burned and destroyed by atmosphere friction.

Presently SOL 1 of the mission is 19th March 2021, which will be considered as Landing SOL.

Currently the Oxia Planum region is considered ad the primary landing site option, Mawrth Vallis is the backup landing site. Figure 1.2 shows the candidate landing sites on the Mars soil.
Oxia Planum has a latitude of 18,159°N and a longitude of 335,666°E with approximate ellipsoidal shape with axes of 120 and 19 km.

On the Martian soil the LP unfolds the appendices: solar arrays, ramps and antennas. The DM continues to supply power to the RM through the umbilical. In a first RM check-out after landing the Ground station ensure that the rover is healthy, with all the subsystems necessary for the Egress running. Afterwards the Rover UHF communication is activated. If it works the umbilical separation occurs and the RM becomes independent. After deployment of its solar array and its locomotion system, the RM is ready for Egress. During this first phase of the mission, cameras on the Rover make acquisition, permitting to Ground operators to determine the safety of a front or rear Egress.

Once the six wheels of the rover are on the Martian soil, the handover happens: ESOC/-MOC passes the operation control to the ROCC an to the SPOCC, which, so far, had a supporting function only. From now on the ROCC has total control of the Rover operations on the Mars surface, and the RSM begins. ESOC continues to support and control communications between the ROCC and the 2016 TGO Data Relay.
At this point the RM has to depart from the LP, to reach a region far from rocket and

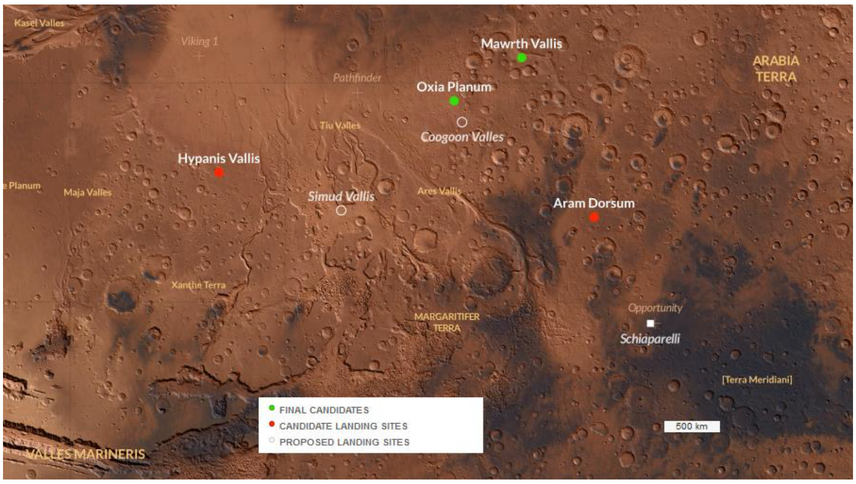


Figure 1.2: ExoMars candidate landing sites with the main choices in green (From http://openplanetary.org/opm/#4/7.36/-21.62).

terrestrial contamination. When the RM is approximately 60 m far from the platform, the ALD (Analytical Laboratory Drawer) commissioning begins with the Blank Sample analysis. A successful test result demonstrates that, from this stage, scientific results can be trusted, as no organic compounds have been brought on Mars from Earth. The Rover Module and the elements interfacing with the future Martian samples are clean if all instruments read *no life* and *no organics*. Failure to obtain this first reading may invalidate any later search for life findings.
After that first test commissioning of the Drill, the SPDS (Sample Preparation and Distribution System) and the PPL (Pasteur Payload) occurs.

Once the RM is stable and the scientific payloads have been activated, the survival priority must consider the objectives dictated by the scientific team. The Rover Surface Operations Phase begins, including Rover mobility (travel to a target) and scientific investigation. This phase nominally lasts 204 SOLs, and represents the main phase of the whole mission which lasts 218 days.

1.2 Rover Module system

From a functional point of view the Rover Module is composed of three major elements: the Rover Vehicle (RV), the Payload Support Function (PSF) and the Pasteur Payload (PPL).

The RV is designed to support and provide resources to the scientific payload instruments suite and to move on the Martian terrain and reach sites of scientific interest.
The RV owns the following subsystems:

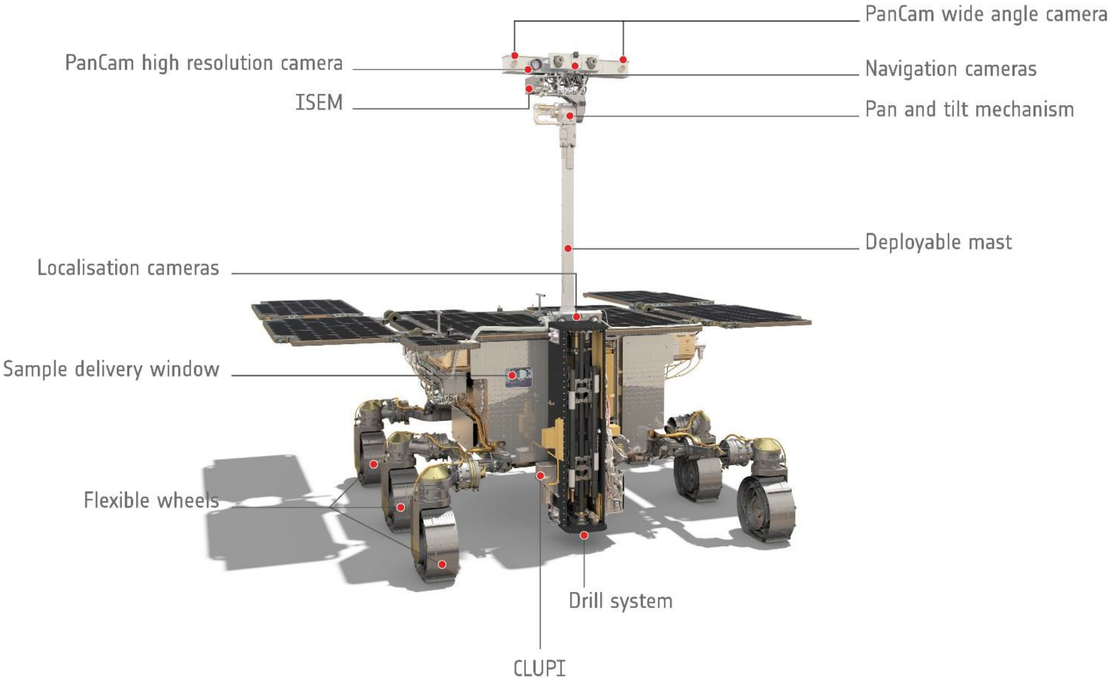


Figure 1.3: ExoMars Rover Module front view (Credit: ESA).

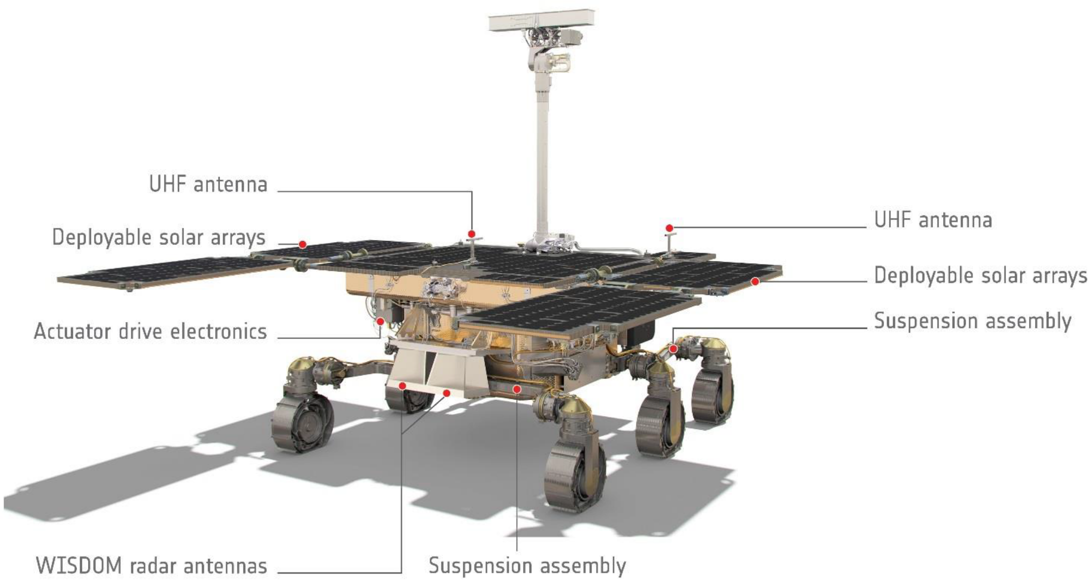


Figure 1.4: ExoMars Rover Module rear view (Credit: ESA).

- The Data Handling s/s, allowing to exchange locomotion, navigation and scientific data with the Ground.
- The Power s/s with its power lines and batteries.
- The TT&C s/s, managing the UHF communications with the orbiter.
- The Thermal s/s, regulating heating and maintaining operating temperatures.
- The ADE(s) s/s, controlling all the Rover moving parts: the Mast, the Solar Arrays and the Locomotion system.
- The Mobility s/s, controlling the Rover locomotion to follow the safe path decided from the Ground. It uses a IMU, a NavCam (the Navigation camera, a stereocamera generating stereo pictures, from which Ground can reconstruct DEM of the terrain up to 20 m safe radius), and a LocCam (the Localisation camera, which provides the attitude with respect to the terrain).
- The Solar Array s/s, management of solar panels.
- The Mast assembly s/s, including a Mast and a PTU (i.e. the pan and tilt actuators), and managing the deployment of the Mast.

The Locomotion system consists of 6 wheels and drive, steering and deployment actuators. The deployment actuators offer the possibility to perform wheel-walking manoeuvres, and so the Rover can move like on legs as a wheel-walking vehicle. This implementation has some advantages with respect to the rolling locomotion mode, especially in some operational scenarios considered hazardous, such as entrapment in sand, up-slope traverse and overcoming steps.

The PSF is used in support of the scientific instrumentation, and it aims at collecting samples and distributing them to the right experiment payload.
The individual PSF elements are:

- The Drill, allowing the sample acquisition, drilling up to 2 meters in the Mars surface.
- The Sample Preparation and Distribution System (SPDS), receiving and preparing (i.e. it crushes, powders, and flattens) the samples and distributing them to the selected scientific payload.
- The Mast which supports the NavCam, the PanCam and the ISEM.

The PPL suite comprises 9 experiment payloads which can be classified in two groups: Survey PPLs and Analytical PPLs.
The Survey instruments selects the scientific target and characterizes its geological context:

- The PanCam is a series of cameras, mounted onto the Mast, providing images of the Rover's environment with different filters.

- The WISDOM (Water Ice and Subsurface Deposit Observations on Mars) is a ultra high frequency ground penetrating radar mounted on the rear side of the Rover, providing a detailed view of both the surface layers and the Martian subsoil up to a depth of 3 m, and their structure.
- The CLUPI (Close-Up Imager) is a colour camera for close-ups. It is mounted parallel to the Drill, and shoots images of any target at a distance from 10 cm to infinity.
- The ISEM (Infrared Spectrometer for ExoMars) is mounted on the Mast under the PanCam. It records the spectrum of sunlight reflected from the Martian surface to study its hydration and mineralogy.
- The Adron-RM is a slow neutron detector spectrometer mounted in the Rover body. It is used to search for underground water, since neutrons are only slowed down by hydrogen.
- The Ma_Miss is an infrared spectrometer, embedded in the Drill tip. It performs a mineralogical analysis during the sample acquisition, scanning the borehole wall created during the drilling.

The Analytical instruments conducts a detailed analysis of each collected sample:

- The MicrOmega is a visible and infrared microscope, characterizing the micrometers-resolution-samples, by their geological origin, structure and composition.
- The Raman Laser Spectrometer (RLS) performs the observation of the surface and the subsurface powdered sample, providing geological and mineralogical information, indicators of biological activities.
- The MOMA (Martian Organic Molecule Analyzer) combines the Laser Desorption Mass Spectrometry (LD-MS) and the Gas-Chromatograph Mass Spectrometry (GC-MS), to detect organic products in the collected samples even if they are present at a very low concentrations.

The Analytical PPLs and the SPDS are accommodated within the ALD (Analytical Laboratory Drawer) inside the Rover.

1.3 Reference surface operations overview

The Rover Reference Surface Mission deals with technology objectives (mobility, acquisition of Mars subsoil samples and automatic sample readiness for in-situ analysis) and science objectives (search for evidence of past and present life and analysis of the water/-geochemical environment in the subsurface).

The nominal RSM should last 218 SOLs, ending before the Mars Global Dust Storm Season which starts approximately in February 2022.

The Reference RSF will be composed of 6 Experiment Cycles (E.C). and 2 Vertical Surveys (V.S).. If the RM proves to be robust enough to be able to withstand atmospheric agents, and the instruments with their consumable resources will still be usable, the operative period on the Martian surface of the ExoMars Rover could be extended.

The Experiment Cycle is the set of operations necessary to select, approach and analyse the scientifically interesting site. Each E.C. consists of the Long Travelling phase, to move from one area to another, and the Measurement Cycle phase, which involves all the PPL equipment. In this phase one superficial sample and one from 150 cm depth are collected and analysed.

The scientific objective of the Vertical Survey is to investigate the geochemical, biological, hydration and oxidant environment with respect to the depth of the Martian subsurface. Each V.S. collects samples at different depths (0, 50, 100, 150and 200 cm) and analyses them with ALD instruments. The five samples are collected at the same point, and analysis is carried out before the next sample is gathered.

1.3.1 Long Travelling

The Experiment Cycle crossing phase of the Rover moving from one site of interest to the next is defined as Long Travelling. These scientific investigation sites are chosen from the Ground.

The Rover nominally covers a maximum of 100 m per SOL, but it is possible that this distance is distributed over several SOLs, depending on the distance between two identified areas of interest.
It is crucial to take into account the limitations and difficulties of blindly selecting a Safe Path from the Ground. The determination of waypoints is based only on pictures and DEMs built by Ground on the basis of the stereo images collected by the cameras.

The first E.C. should take place as close as possible to the Lander. Nevertheless, it is necessary to travel a distance of at least 60 m away from the contaminated landing area.

The Long Travelling phase ends nominally 20 m from the area where the E.C. target was set. From this distance the Measurement Cycle phase begins.

At the end of each travelling SOL, the Earth must receive a required set of data from the Rover and the TGO.
The Rover, in addition to the images acquired, must transmit the Path Following Data: Localization Data and Route Data. The Localization Data are composed of the absolute attitude - $roll$, $pitch$ and yaw - and the relative position - x and y - with respect to the SOL starting point. The Route Data reports encountered errors relative to the safe corridor to be followed, the controlled trajectory and slippage.
The Orbiter sends other data, necessary to support the Rover mission, such as high-resolution satellite images of the area where the Rover has stopped.

Based on the data received, the Ground operators will have to determine the Rover absolute position and its absolute heading with respect to the Mars surface. Afterwards, they will identify the corrective path to recover the errors.

1.3.2 Measurement Cycle

During this Experiment Cycle phase the engineering survival priority must consider the scientific objectives. The PPLs are used and most of the TM data will be made up of the scientific data of this instrumentation.

A typical Measurement Cycle starts at 20 m from the site to be examined, with a PanCam panoramic acquisition and an ISEM acquisition. The latter records spectra emitted by the same elements photographed by PanCam. At this moment, the Adron-RM is switched on, and set to continuous scan mode for all Rover working hours.

The Rover approaches the site to be investigated and stops 3 m from there. PanCam and ISEM re-acquire images and spectra. Afterwards the Rover starts to move to the target. During the approach, the WISDOM performs a Simple Sounding every 50 cm.

When the Rover reaches the spot to be examined, the PanCam acquires an overview, and the CLUPI takes detailed images of the site. Based on these images, the Ground operators decide where to collect the Surface Sample. The sample is collected and the CLUPI takes a picture of it. Then the Surface Sample is sent to the SPDS which prepares and distributes it to the appropriate payload(s). The analysis of the ALD instruments is performed: MicrOmega, RLS and MOMA act.

To identify the drilling area where to collect the Sub-Surface Sample, at most 10 m away from the Surface Sample area, the WISDOM performs a Full Sounding in a WISDOM grid. It scans every 10 cm in an area of 5 $m \times 5$ m with rows 1 m apart. Meanwhile, the Adron-RM continues to acquire data.
Examining those WISDOM scans and analysing the PanCam images, Ground Operators decide where to collect the Sub-Surface Sample. Assuming that the Rover can drill 50 cm per SOL, collecting the sample at 1.5 m depth will take three SOLs.

During the drilling the Ma_Miss acquires its measurements on the borehole wall.

Once collected, the Sub-Surface Sample is sent to the SPDS, after the CLUPI has made its acquisition. The ALD analysis begins: MicrOmega, RLS and MOMA perform their own tests.

The Measurement Cycle lasts several days. Its duration depends on many factors, including the Martian environment encountered by the Rover and the fluency of the Rover-Ground communication.

The main constraints for a seamless Measurement Cycle are: the critical size of generated data that can be transferred to the Earth each SOL, the Rover resources available, and the TGO visibility.

Critical data generated by the Rover depends on the SOL type, i.e. if the working day is spent travelling, drilling or analysing. In addition to the Critical Scientific Data, Essential HouseKeeping Data and Navigation Data must always be sent.
The main resources required by the Rover are time and energy. The energy generated and the working time depend on the sunrise and sunset time as well as the Orbiter overflight time on the Rover area.

1.3.3 Vertical Survey

When an E.C. achieves interesting results, it is possible to perform a Vertical Survey, hence selecting a drilling target very close to the last Measurement Cycle site.

During the V.S. there will be more underground drilling to collect a total of five samples: the superficial one at 0 *cm* and the sub-superficial ones at 50, 100, 150 and 200 *cm* depth. Once a sample is collected the ALD performs its analysis. The Drill is then repositioned with extreme precision in the hole previously created and drills deeper to collect the next sample.

After the E.C. achieves interesting results the Rover moves at most 10 *m* to reach the V.S. drilling site. Unlike the target approaching in an E.C., in this crossing the WISDOM and the Adron-RM do not work, as this area has already been characterized by the previous Measurement Cycle.
At site of drilling, the CLUPI will take a detailed picture of where the samples will be collected. At this point a sequence of operations begins. These are very similar to that of the Measurement Cycle, with four Sub-Surface Sample collected at different depths instead of one. In this sequence all the ALD instruments analyse the five samples.

1.4 Rover Module commandability

The Rover can perform Actions, Tasks and Activity Plans ordered from the Ground.

The Action is an elementary operation identified by parametrized specifications. These are the preconditions that must be reached by the system before the Action starts, and the postconditions that must be satisfied when the Action ends. The Action can also end with an error when, after a default timeout, the postconditions are not achieved or are achieved with exceptions. Usually the Action involves only a subsystem.

The Task is an operation of varying complexity. It often consists of a set of Actions that follow a hierarchical and structured order to get an objective. These logical and temporal steps allow controls and decision points, providing predefined corrective Actions in case there is a faulty ending of an Action. Often the Task concerns two or more subsystems.

The Activity Plan (AP) consists of a set of Activities (both Actions and Tasks) that must reach an objective considering the operational constraints encountered, including available resources and communication needs.

In the ExoMars Mission the ROCC has the Activity Plan generation and uploading responsibility, whereas the OBSW (On-board SW) installed in the RM OBC (On-board computer) has the Activity Plan execution responsibility.

ROCC operators must create and validate the APs, with the purpose to detect and isolate anomalies, and trying to recover them. In writing the AP they must also predict and optimize the available Rover resources, in terms of energy, time and data.

The RM will not be equipped with artificial intelligence, it will be able to follow a sequence of event-based autonomous operations. The OBSW will guarantee a robust, but flexible, control function, taking into account the usage of available resources and the ability to recover non-hazardous failures.

This type of autonomy will require an enormous effort during the definition of various activities concerning each phase of the mission. The OBC will execute the operational sequences contained in the AP, following a series of commands stored on-board in the Event/Action Table (EAT), and taking into account its interaction with the Martian environment, unknown a priori.

This Near-autonomous Rover Operations Concept will control the possibility of performing the operations, according to available resources, and guarantees the safety of the rover in travel phases.

The Rover autonomously implements the following three Tasks, to reduce the difference between the desired and the real position:

- Tilting Control: prevents the Rover topping if the inclination - roll or pitch - exceeds a default threshold.
- Slippage Control: prevents the Rover sinking if it slips on the sand.
- Path Corridor Control: prevents the Rover deviation from a corridor containing the Safe Path chosen by the Ground.

The Safe Path is identified as a trajectory free of obstacles higher than 25 cm or crevasses, and it can be blindly followed by the Rover.

Beyond these few controls, Ground operators must drive the Rover point-to-point. To do this they send an AP every SOL.
The decisions taken from the Ground are based on data and images received by the Rover cameras and the TGO: the NavCam generates images with a resolution of $2-5$ cm up to 10 m from the Rover, the LocCam generates images with a resolution of $5-10$ cm up to $20-30$ m from the Rover, depending on the obstacles. Lastly the TGO generates Orbital images with a resolution of $50-100$ cm up to 100 m from the Rover. These images are processed from Earth, transformed into DEMs and allow operators to define the Safe Path and the dead-end areas, by combining the last 3D models with those already obtained by previous SOLs.

In conclusion, the Ground-defined plan can only be considered really safe within a radius of about twenty meters, where the very fine NavCam DEM and the fine LocCam DEM are used.

Each AP sent from the Ground contains engineering and scientific activities for the next two operational SOLs. The first one is based on the actual data received on the previous SOL. The second one contains a back-up activity plan in case the communication with Ground can not take place, avoiding to leave the Rover idle.
Each AP can be complemented with a set of alternatives. The Alternative APs are sent in a sequential use order. The Rover performs the alternative ones in case it does not have the resources - time and energy - necessary to the nominal one.

In the Ground planning a distinction is made between Tactical and Strategic Planning.
Tactical Planning involves short-term activities and identifies the operations to be performed in the two following SOLs. However, it is important that the ROCC operators take into account the medium-term objectives. Operators must identify the activities of the next E.C. or the next V.S., and determine a strategic process involving more SOLs.

The Strategic Planning is performed during the working hours of the office, and operators have to:

- generate long-term strategic plans;
- plan communications between ground teams to coordinate RM and LP missions;
- monitor the progress and success of the mission in its entirety;
- validate new activities or operational sequences;
- update the AP models.

The Tactical Planning is performed in the Main work shift, and operators have to:

- download the RM Critical TM;
- assess engineering and scientific data;
- plan the scientific activity;
- refine and validate the AP models generated during the Strategic Planning;
- review the AP file;
- generate the sequence of commands that allows the Rover OBC to execute the AP;
- integrate and validate the sequence of commands;
- transmit the TCs to the TGO.

The AP sent at the end of the Tactical Planning is a text file written in Rover Activity Plan Description Language (RAPDL).

The AP contains:

- a series of nominal activities;
- a list of alternative activities, which are executed if the nominal one is terminated before the end of the working-time or if there are limitations in executing the nominal one, such as lack of time or energy;
- TC sequences implementing the Activity Plan;
- control laws;
- information regarding priorities, constraints, configurations and limitations, validating the operational sequence and regulating a possible re-planning of the AP execution.

RAPD Language

The RAPDL (Rover Activity Plan Description Language) allows the definition of mission activities and their synchronization with events not known a priori. The activities can be performed sequentially or simultaneously. This is the case of long-lasting activities that involve different subsystems and time saving is needed, or when collaboration is needed between different subsystems. Additionally, it is possible to use conditional execution, in case the execution of a follow-up task or action is needed.

In the following examples of different declaration of commands are shown. The RAPDL uses them to organize and synchronize the activities execution. An AP is a list of instructions that are read, interpreted, and evaluated in the order in which they have been written.

`EXEC Activity #n, RV_WakeUP;`
This EXEC declaration means: execute the activity with id *Activity #n*, calling a list of on-board stored commands named RV_WakeUP and then pause the AP reading until the activity has been completed. Then continue with the activity *n+1* in a sequential way.

`START Activity #m, RV_Prepare4Travel;`
This START declaration means: start executing the task activity with id *Activity #m*, calling a list of on-board stored commands named RV_Prepare4Travel and then continue the AP reading, evaluating and immediately executing the activity *m+1*, simultaneously with activity *m*.

`WAIT_ACTIVITY_END Activity #m;`
This WAIT_ACTIVITY_END declaration means: before continuing with the AP reading and executing the next activity, wait for the activity with id *Activity #m* to be completed.

`WAIT_EVENT <Event_id>;`
This WAIT_EVENT declaration means: before continuing with the AP reading and executing the next activity, wait for the `<Event_id>` event, predefined in the EAT, to occur.

`CHECK_ACTIVITY Activity #t;`
This CHECK_ACTIVITY declaration means: interrogate the result of the activity *t*, which can be a status (stand-by, running or terminated), a flag (`ERF` - Execution Returned Flag), or a value (`ERV` - Execution Returned Value). Based on this result, the MMS performs some controls.
For example:

```
CHECK_ACTIVITY Activity #t;
     IF  ERV == xxx THEN
         EXEC/START ...
     ELSE
         EXEC/START ...
     ENDIF
```

The `ERF` return could be equal to `OK` - activity `t` ends with nominal conditions or with Transparent Anomalies, which do not imply stopping the plan - or equal to `ERROR`. If an `ERROR` occurs, the AP reading ends and the Rover switches into Safe mode. If a Non-Time Critical Anomaly occurs, the Rover enters in a low-power state, activating the Lite Safing mode. If, however, Time Critical Anomaly occurs, the Rover enters into stand-by, activating the Full Safing mode. Only the survival engineering subsystems work at nominal regime, the OBC is on and registers TM and the Rover waits for communications. After an `ERROR` occurs the RM always stops and waits for a Go-Ahead from the Ground, which will make a decision after a data analysis.

To sum up, the OBSW reads the AP sequentially, satisfying the indications, until it encounters an `ERROR` or until it reads `END_SOL`, indicating the end of the RAPDL file. If the MMS reaches this final statement, the AP has been evaluated and executed without anomalies.

Figure 1.5 shows an Example of an Activity Plan represented in macro-blocks and Figure 1.6 shows the same AP in RAPDL.

Each rectangle process block in Figure 1.5 represents a set of operations involving the communications, the RV, the SPDS and the PPLs. Note that this example mentions the Autonomous Navigation execution, which was an ExoMars objective in an embryonic mission phase now deleted.

Usually, before starting a complex sequence of activities, the **`MMS_Validate`** Task is executed. In Figure 1.6 you can see Validation Points calling the statement: `EXEC Activity_n MMS_Validate(options)`. It compares the runtime available resources and the resources necessary to the following sequence of activities as expected by Ground predictions. If time and energy are not sufficient, the AP reading is stopped and the alternative RAPD text file is loaded. The **`MMS_Validate`** is shown as a diamond decision block in Figure 1.5, with the two alternative paths.

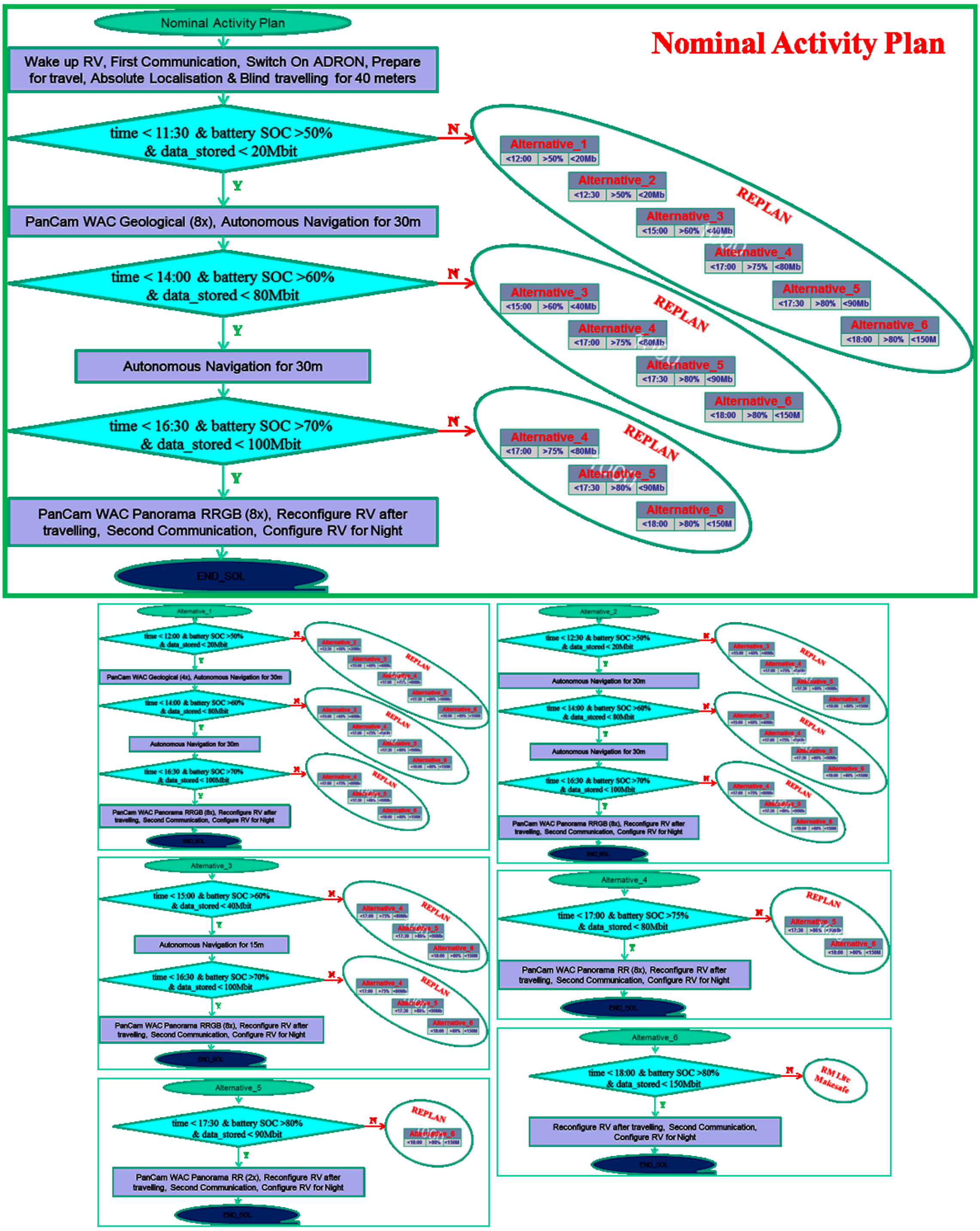


Figure 1.5: Activity Plans for Long Travelling in macro-blocks (Credit: TAS-I).

```
#==========================================
# Long Travelling Sol - Example of Nominal Activity Plan:
# - Travel 40m path uploaded +
# - Validation point +
# - PanCam WAC Geological 8 positions +
# - Travel 30m Autonomous Navigation +
# - Validation point +
# - Travel 30m Autonomous Navigation +
# - Validation point +
# - PanCam WAC RRGB 8 positions
#==========================================

# Wait until sunrise
EXEC    Activity_1,
        MMS_WaitAbsTime(0,8,0,0);

# Wake up rover task
EXEC    Activity_2,         RV_WakeUp;

# Prepare for communication
EXEC    Activity_3,         RV_Prepare4Comms;

# Communication performed when hail detected by the
Transceiver

# Wait until communication is performed & reconfigure
transceivers and OBC
EXEC    Activity_4,
        MMS_WaitAbsTime(0,8,30,0);
EXEC    Activity_5,         RV_PostComms;

# Wait 9:15am to start operations
EXEC    Activity_6,
        MMS_WaitAbsTime(0,9,15,0);

# Start Warmup and switch Mobility Equipment &
reconfigure OBC
START   Activity_7,         RV_Prepare4Travel;

# Warmup, switch on and start passive measure with
ADRON
EXEC    Activity_8,         ADRON_SwitchOn;
START   Activity_9,
        ADRON_PassiveMeasure(level1, disclevel1);

#Wait until the RV is ready to travel
WAIT_ACTIVITY_END      Activity_7;

# Perform Absolute Localisation and 40m travelling
BLIND MOTION: a path is uploaded and the rover does
not stop to compute DEM.
EXEC    Activity_10,        GNC_AbsLocalisation;
EXEC    Activity_11,        GNC_FollowNoCheck(40,
32, 10, SINGLE);
EXEC    Activity_12,        RV_SwitchOffMobility;

# Validation point:
#         - <time shall be less than 11:30>, <battery
SOC shall be more than 50%>, <data_stored shall be
less than 20Mbit>)
#         - in case of validation failure replan is foreseen
through 6 alternatives (priority: Alternative_1 up to
Alternative_6)
EXEC    Activity_13,        MMS_Validate(11.5, 50, 20,
Alternative_1, Alternative_2, Alternative_3,
Alternative_4, Alternative_5, Alternative_6);

# Acquire a full sequence (8x) of WAC images with
geology filters
EXEC    Activity_14,        PANCAM_WAC_Geol(8,
<Position>, <IntegrationTime>);

# Perform 30m autonomous navigation travelling (up to
70m far away)
EXEC    Activity_15,        RV_Prepare4Travel;
EXEC    Activity_16,        GNC_AutoNav(30, 32, 10,
SINGLE);
EXEC    Activity_17,        RV_SwitchOffMobility;

# Validation point:
#         - <time shall be less than 14:00>, <battery
SOC shall be more than 60%>, <data_stored shall be
less than 80Mbit>)
#         - in case of validation failure replan is foreseen
through 4 alternatives (priority: Alternative_3,
Alternative_4, Alternative_5, Alternative_6)
EXEC    Activity_18,        MMS_Validate(14, 60, 80,
Alternative_3, Alternative_4, Alternative_5,
Alternative_6);

# Perform 30m autonomous navigation travelling (up to
100m far away)
EXEC    Activity_19,        RV_Prepare4Travel;
EXEC    Activity_20,        GNC_AutoNav(30, 32, 10,
SINGLE);

# Validation point:
#         - <time shall be less than 16:30>, <battery
SOC shall be more than 70%>, <data_stored shall be
less than 100Mbit>)
#         - in case of validation failure replan is foreseen
through 3 alternatives (priority: Alternative_4,
Alternative_5, Alternative_6)
EXEC    Activity_22,        MMS_Validate(16.5, 70,
100, Alternative_4, Alternative_5, Alternative_6);

# Acquire a full sequence (8x) of WAC images with left
Red filter and right RGB filters
EXEC    Activity_23,        PANCAM_WAC_RRGB(8,
<Position>, <IntegrationTime>);

# Switch off ADRON
EXEC    Activity_24,        ADRON_Abort;
EXEC    Activity_25,        ADRON_SwitchOff;

# Prepare for dozing
EXEC    Activity_26,        RV_Prepare4Dozing;

# Wait until planned communication window &
reconfigure transceivers and OBC
EXEC    Activity_27,
        MMS_WaitAbsTime(0,18,0,0);

# Prepare for communication
EXEC    Activity_28,        RV_Prepare4Comms;

# Communication performed when hail detected by the
Transceiver

# Wait until communication is performed
EXEC    Activity_29,
        MMS_WaitAbsTime(0,18,30,0);

# Prepare for night
EXEC    Activity_30,        RV_Prepare4Night;

END_SOL;
```

Figure 1.6: Activity Plans for Long Travelling in RAPDL (Credit: TAS-I).

1.5 TGO data relay orbiter communication link

Communications between the RM and the ROCC are mainly carried out using the ESA 2016 TGO.

At the beginning of the 2019 the satellite should reach its nominal science orbit, allowing its use as a communication relay in the 2020 ExoMars mission. The TGO will have a mean height on Mars surface of 394 km and should perform between 12 and 13 revolutions around Mars per SOL. It ought to see the 2020 Rover from two to three times each SOL. During these overflights the RM, communicating with the TGO, will be able to uplink the TM (HK and scientific data), and downlink the TCs coming from the ROCC.

ESTRACK is the ESA network of tracking stations, with the task of supporting the communication between ESOC and satellites in orbit. It is a worldwide system of 10 ground stations that communicate with the spacecraft by uplinking the commands and downlinking scientific data and other data concerning the satellite health status.
The ROCC operators will communicate directly with the ESOC that, through the ESTRACK, will transfer the data to the TGO.

For the ExoMars mission, the plan is to use three ESA Deep Space Antennas (DSAs), with the additonal support from NASA and Russian DSA.

Figure 1.7 - created with STK - shows the Ground stations which will be utilized during the 2020 ExoMars mission:

- The ESA New Norcia station - DSA 1 - is located in the Western Australia, close to the town of New Norcia.
- The ESA Cebreros station - DSA 2 - is located in Spain, close to Madrid.
- The Malargüe station - DSA 3 - is ESA's newest tracking station and it is located in Argentina, close to Buenos Aires.
- The Russian Deep Space antenna is located at Bear Lakes, near Moscow.

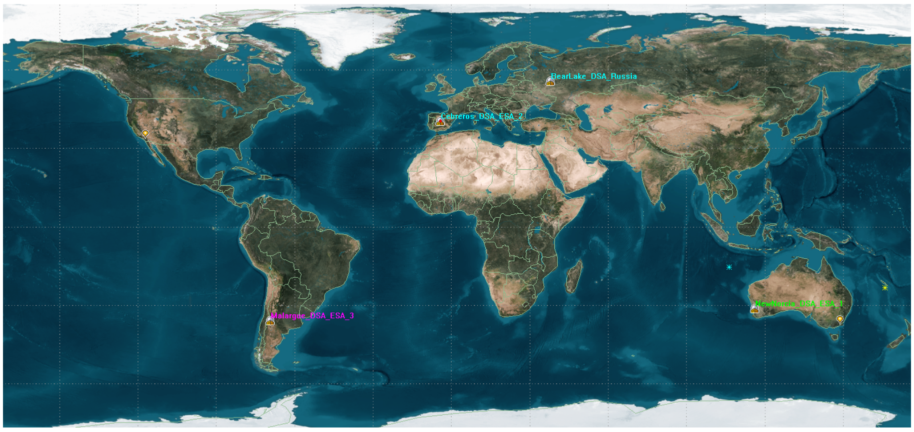


Figure 1.7: 2020 ExoMars STK scenario - Ground stations.

To sum up, considering TGO as the main orbiter supporting the mission, the communications will take place as follows:

$$\text{ROCC} \rightleftharpoons \text{ESOC} \rightleftharpoons \text{TGO} \rightleftharpoons \text{RM}$$

and the communications between ESOC and TGO will be regulated by the three ESA Deep Space Antennas that are part of the ESTRACK network.

In this Section, for the sake of simplicity, it will be assumed that RM and ROCC communicate when the TGO passes on the Rover. Latencies in communication due to these delivery steps will be considered in the following sections.

The ideal sequence starts with the transmission of the TCs from the Ground to the Rover in the Mars morning. During the SOL the Rover has time to execute the plan. In the evening the Earth downloads the TM containing the scientific and engineering data.
Data assessment and planning in the Ground Control Centre have to be completed between the evening over-flight and the following morning pass.

The TGO Data Relay Orbiter does not have a sunsynchronous orbit. Therefore the communication intervals change from time to time in terms of visibility and duration.

The TGO should anyway guarantee two passages per SOL, dedicated to communication with the Rover, and, even if the time between the two passes is variable, the noon-to-midnight passage and the midnight-to-noon passage are accounted for.

For the sake of simplicity, in the example shown in Figure 1.8 it is assumed that the TGO always passes above the RM at 8 a.m. and at 6 p.m. in Mars time.

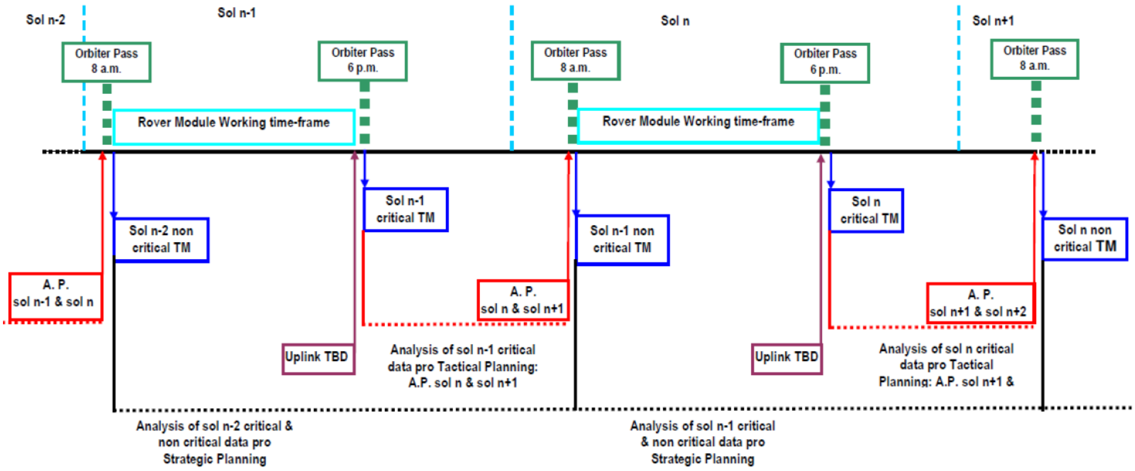


Figure 1.8: ExoMars Rover Mission Planning Cycle Example (Credit: TAS-I).

- At ***SOL n-1*** in the 8 a.m. overflight the RM uplinks Non Critical TM about the *SOL n-2* and downlinks the AP for the *SOL n-1* and the *SOL n*. Then the Rover begins to operate and execute the *SOL n-1* plan, while in the ROCC the new Non Critical data and the Critical data previously received are analysed for the Tactical Planning. In the 6 p.m. overflight the RM uplinks Critical TM relative to *SOL n-1*. During each SOL the ROCC will identify the potential need to exchange communications with the RM during the evening pass. Finally, the Rover enters in night-time configuration. In ROCC the received Critical *SOL n-1* data are analysed for the *SOL n* and *SOL n+1* Tactical Planning.
- At ***SOL n*** in the 8 a.m. overflight the RM uplinks Non Critical TM about the *SOL n-1* and downlinks the AP for the *SOL n* and the *SOL n+1*. Then the Rover begins to operate and execute the *SOL n* plan, while in the ROCC the new Non Critical data and the Critical data previously received are analysed for the Tactical Planning. In the 6 p.m. overflight the RM uplinks Critical TM relative to *SOL n*. During each SOL the ROCC will identify the potential need to exchange communications with the RM in the evening pass. Finally, the Rover enters in night-time configuration. In ROCC the received Critical *SOL n* data are analysed for the *SOL n* and *SOL n+1* Tactical Planning.

A two-SOL plan must always be ready to ensure 48 hours of Rover autonomy.

Chapter 2

ROCC: Rover Operations Control Centre

The Rover Operations Control Centre (ROCC) is hosted in Altec in Turin.
The ROCC task is to control the operational processes of the ExoMars Rover Module from the launch. It will assume absolute responsibility on the RSM, starting from the moment when the Rover has all six wheels on the Martian soil.

There are three main planning approaches used by Ground operators for the different processes: long/mid term strategic operations planning, short term strategic operations planning, and tactical operations planning.

Long/mid term strategic operations

- Before the landing:
  - Identify the main scientific characteristics of the landing site using the orbital images sent from the TGO.
- After the landing and before the Egress:
  - Accurately determine the landing position.
  - Establish a list of interesting areas to reach with the Rover, after the first images received.
- After the Egress and during the commissioning:
  - Determine the location where to run the first E.C..
  - Define hypothetical places where the following E.C.s can be performed.
  - Evaluate how many SOLs may be needed to reach each target.

- Before the end of each E.C./V.S.:
  - Rectify the location of the next target.
  - Refine the next mission phases.

Short term strategic operations

- Provide any warning and update to the tactical planning phases, based on the trend analysis of the operations already performed.
- Assess and track the success and failure of activities.

Tactical operations

STEP 1: Retrieve and Process

- The TM arrival at the ROCC from the ESOC denotes the begin of the Tactical planning. Ground operators receive HK data, scientific data and images. HK packages are de-commuted, calibrated and archived. Engineering and scientific files are reconstructed, distributed and archived.

STEP 2: Access, Visualize and Analyse

- The HK data are analysed and assessed by the engineering and scientific teams, who are in charge to produce the "Health Status and Assessment Reports" about the RV and the PPLs. This step ends with the "Rover Status Meeting", when the results of engineering and scientific evaluations are summarized.

STEP 3: Propose, Integrate and Agree

- This step is based on the "Rover Status Meeting" minutes. If it is possible to proceed with the nominal planning path, the AP produced by the short term strategic planners can be used as they are, with minor modifications done on the basis of the data received from Mars. In case the Rover TM has revealed contingencies or anomalies on board, an AP from scratch has to be prapared and validated.

STEP 4: Validate and Simulate

- The AP is validated using the Rover Operational Simulator, and the resources of the rover are estimated to be sufficient to execute it in a SOL. In case of errors or 'major' problems the AP is sent back to the STEP 3, and changes will be made. At the end of this step the "Rover RAPD Uplink Report" is generated. This includes a list of activities and their duration, the global energy and memory parameters used, and charts highlighting the critical parameters. The Report will be analysed in STEP 1 of the next cycle, to compare the estimated resources needed with the TM generated then.

STEP 5: Pack and Deliver

- The AP is translated into a series of TCs and transmitted to ESOC.

2.1 ROCC responsibility during RM operations

The ROCC and the other Ground segment teams share the responsibility of the Rover during the different phases of the mission.

The operational phases of the mission can be divided based on key events such as:

- Launch;
- Cruise;
- DM separation;
- Landing;
- Rover activation and check-out;
- All of the six Rover wheels laying on Mars surface;
- 218th SOL;
- Disposal;

2.1.1 Pre-launch phase responsibility

The ESOC/MOC has the Spacecraft Composite (RM and LP within the DM, and the CM) responsibility before the launch, but the ROCC give its support in all which concerns the ExoMars Rover. The ROCC continuously communicates to ESOC any activity that the Rover Module must perform in the pre-launch phase.

2.1.2 Cruise phase responsibility

During the Launch and Early Orbital Phase (LEOP) the Rover should not perform any operation and therefore remains in an OFF status. The ROCC remains operational in case the ESOC/MOC, following the Spacecraft Composite operations, needs it.

During the Cruise Phase, lasting approximately eight months, the ROCC is responsible for the RM, but it must agree with the ESOC/MOC the Rover activity so as not to undermine the Spacecraft Composite needs and constraints.
During the cruise the RM will be switched off most of the time. It will be switched on

occasionally to perform at least three check-outs to confirm the healthy status of the Rover, to update its SW (if needed), and to recharge and balance the batteries. On each of these occasions the ROCC TCs will be sent to ESOC, which will send them to the DM. The RM will then be controlled by the OBC of the DM, connected to it by the umbilical. Three check-outs are planned in three key moments of the cruise: the first during the Spacecraft Composite commissioning, the second in the middle of the interplanetary cruise, the third before the DM separation from the Spacecraft Composite, previously to the EDL Phase. During these controls the ROCC ensures that the health and status of the Rover are nominal and otherwise it must organize troubleshooting for the detected problems.

2.1.3 DM phase responsibility

In the DM phase the DM carries the Rover, lodged within the LP. Its separation from the Spacecraft Composite, opens this phase.
This macro-phase includes minor ones covering very critical operations: the DM-CM separation, the DM Coast, Entry, Descent and Landing (CEDL) phase and the Post Landing To Egress (PLTE) phase.

The ESOC/MOC is responsible for DM operations, and is mainly supported by the SPOCC, responsible for the LP. Since the RM is switched off until the touchdown, no ROCC operations are planned in the CEDL phase, although it must be ready to give direct support to the ESOC if requested.

During the landing the Rover is inside the LP, with all the appendices stowed. The PLTE phase begins after the landing with the automatic stabilization of the LP, the automatic opening of its ramps, its Solar Array and its antennas, and the removal of the RM constraints. The RM, still connected to the DM through the umbilical, turns on independently and awaits the first commands from the Ground. The stowed RM operates using energy from the LP, which generates power through its deployed Solar Array. The Rover generates the TM that contains its health status after landing and sends it to the Ground during the first overflight of the TGO. Since the RM turns on, the ROCC communicates to ESOC the operations that the Rover must perform, but the ESOC/MOC is still responsible for the whole DM, and the RM continues to be controlled by the DM OBC. When ROCC operators have made sure that the landing configuration and the state of health of the Rover are nominal, they begin to generate the plan for the following SOLs, that will lead to the RM Egress from the LP. As a first step the ROCC orders a check-out very similar to those that the Rover has performed during the cruise, but with the possibility of checking some elements (eg. the RM Solar Array) that were not controllable within the Spacecraft Composite. The goal of this first post landing check-out is to confirm that the RM subsystems necessary to support the Egress are working.
If the outcome of the check-out is positive, the ROCC launches Egress operation sequence:

- The LocCam and the NavCam acquire images with the mast stowed;
- The Mast is deployed and the NavCam reacquires images;

- The front and the rear Wheel Hold-Down Mechanisms are released;
- The Locomotion subsystems are deployed and the Rover rises;
- The Solar Array is deployed;
- The UHF communication is activated in order to be tested before the RM disconnects from the DM and its communication system;
- The middle Wheel Hold-Down Mechanism is released, the RM is now free to move;
- The umbilical separation occurs, from this moment on, the Rover is commanded by its OBC and communicates through its own TT&C s/s;
- The LocCam and the NavCam acquire images with the Rover upright;
- The Rover front or rear Egress occurs.

These operations require at least five Ground go-aheads, and then will be performed in at least six SOLs.

When the Rover has all its wheels on the Martian soil, the handover between ESOC/MOC and ROCC is accomplished and the Rover starts operating completely led by the ROCC.

2.1.4 Surface phase responsibility

The Surface phase starts immediately after the Rover Egress from the LP. The responsibility for the Rover Mission is completely handed over to the ROCC.

This phase includes all the RM activities on the Mars surface from functional commissioning onwards. As soon as it descend the platform, the Rover must move away from the area infected by engines, in order to guarantee the ALD commissioning in a decontaminated area. Then the ROCC operators carry out the scientific investigation on Mars by combining the possibility of performing in-situ scientific analysis, the ability to move the Rover, and to drill and collect samples in the Martian subsoil.

2.1.5 Extended Surface and Disposal phases responsibility

At the end of the reference RSM, on the 218th SOL, if the Rover is still able to work the ROCC operators will try to exploit the opportunities to use the PPLs.

The duration of the Extended Surface phase is unpredictable, but the ROCC operator will need to understand when the RM is about to end its potential. At the end of the Rover scientific activities, it will be guided as far as possible from interesting experimental sites and then shut off properly for its final disposal. The ROCC has the responsibility of the Rover Disposal.

Chapter 3

Managing operations and Ground teams in a robotic mission

Unlike other missions in deep space, Ground operators in a robotic mission must interact daily with the Rover. Every day the operation team must evaluate the health of the Rover, update the AP for the following SOLs, validate that vehicle resources are sufficient to carry out the plan

It is important that during the tactical planning process, operators look some SOLs ahead, and have a clear strategic planning.

Ground operators of other ExoMars-like missions, such as those working for Curiosity (MSL Rover) and for Spirit and Opportunity (MER Rovers), are regularly switched between strategic and tactical processes to ensure that strategic process goals and tactical process needs go hand in hand.

Tactical and strategic processes have intensive workloads, with limited interruptions and tight deadlines. To avoid errors that could put the Rover at risk, the number of consecutive tactical work cycles for a single person is limited. Nevertheless, there is the need for continuity from one day to the next, and from one team to the next. The high number of shifts to fill, the difficulty and uniqueness of every day planning, and the great mental fatigue of tactical planning members make the problem of scheduling rather daunting.

There are several personnel planning systems that handle most of the constraints encountered in a mission of this type, but none of these meet all constraints.

The most important constraints to consider are:

- Competences: specific functions or roles for which personnel is qualified, and which must always be covered in each shift.
- Off-days: rest days when a person cannot work.
- Week days: days of the week in which a person can generally be considered available.

- Shift-weighting: most challenging days weigh heavier in scheduling.
- Duty cycle: total number of shifts that can be covered by a person in a given period of time are limited, to avoid burning out the personnel.
- Graceful constraint descope: each person can list the constraints in order of importance, starting from the rigid ones without the possibility of negotiation.

The tactical planning should end before the Mars-morning relay satellite overflight on the Rover, in order to load the generated AP. Based on this condition, the shift are synched on the Mars clock, working Mars time.

If a sunsynchronous data relay satellite is used, the first issue arising is that the Martian SOL and the Earth day have different lengths. The Martian SOL is approximately 40 minutes longer than the Earth day. For example, if in a given day 6:00 Earth time is synchronized with 7:00 Mars time, the day after at 7:00 on Mars will be roughly 6:40 on the Earth, then 7:20 the next day, and so on. So the schedule will shift by 40 minutes each day. The second problem arising in the case of the TGO used as data relay, is that it is not sunsynchronous, but overflight takes place at different times during the day. Therefore, shifts synchronized with satellite passes slide in the day.

The start time of the shift in constant movement is uncomfortable for the operator. However, at the beginning of the mission, the operations team has little experience with both the planning process and the management of the vehicle. Therefore, working Mars time gives more time to the planning process, operators respond to new data quickly and consistently, benefiting productivity and scientific achievement.

Working 5 days a week, with stable shift times during normal working hours, is certainly a more sustainable approach. The staff follows well-established patterns of sleep and family interaction, resulting in a more stable mentality. The experience with the various Ground operators for Mars Surface Missions shows that a more normal and sustainable operational program leads to less personnel turnover, as workload becomes less challenging, and helps to reduce operating costs. Furthermore, the reduction in fatigue and disorientation seems to result in less command errors. In order to keep shift times within a stable range in the Earth day, the mission must give up the ability to react promptly to new data, accepting a reduction in operational efficiency.

Currently, there are different operations schedule modes defined for MER and MSL: Mars time, Modified Earth-time 7 days/week, and Modified Earth-time 5 days/week.

Modified Earth-time has a given shift duration, an *earliest start time*, a *latest start time*, and a *preferred start time*, and is organized in a 38 day cycle.

The *preferred start time* is the one of the shift during normal working hours (eg 8:00 a.m).. To maintain the shift in a sustainable time, its start time can be set between the *earliest start time* (eg 6:00 a.m). and the *latest start time* (eg 11:00 a.m)..

"Nominal SOLs", "slide SOLs", "restricted SOLs", "tight SOLs", and "soliday" are classified based on the times of TM arrival and of TCs forwarding, (see [13]).

"Nominal SOLs" are those with the *preferred start time* just after the TM downlink, and the tactical process is completed comfortably before the end of the shift and TCs uplink time. In other words, the shift in normal working hours fits perfectly into the downlink-to-uplink window.
The downlink time moves in the day, and can be accomodated by a later shift start, until the latter reaches the *latest start time*. These planning days are called "slide SOLs".
When the downlink time exceeds the *latest start time*, the shift start time goes back to the *preferred start time*. As long as the downlink time is not too late in the day, so that a shift starting at *earliest start time* can accommodate it, the planning cycle is called "restricted SOLs".
"Tight SOLs" are those that occur when shift start from the *earliest start time* to the *preferred start time*, during a period that best accommodate downlink time.
A "soliday" (a no-planning day) occurs between "restricted SOLs" and "tight SOLs", hence every 38 days (there are 37 sols scheduled during a 38-day cycle).

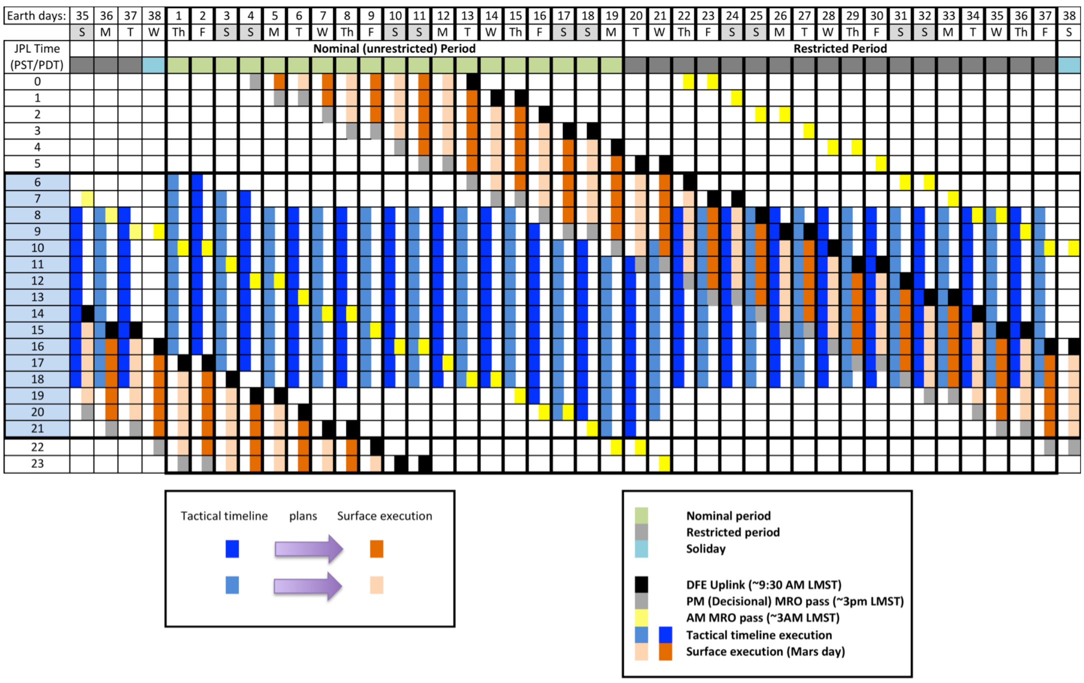


Figure 3.1: 7 Day/week Modified Earth-time schedule in 38-day cycle (Credit: [13] *Sharon Laubach "Calculation of operations efficiency factors for Mars Surface Missions"*).

Figure 3.1 shows the progression in the Earth time day of the downlink period (gray bar) and the uplink period (black bar), which slide following the morning overflight of the MRO data relay (yellow bar). Orange bars designate the Rover working hours on the surface of Mars; blue bars represent the Earth tactical planning shift.
For the sake of simplification, in this Figure, "nominal", "slide", and "tight" SOLs are all designated as "Nominal (unrestricted)" and coloured in green, "restricted SOLs" in dark

grey, and the "soliday" in turquoise.

3.1 Shift schedule approach during ExoMars 2020 Tactical Operations

Every day the ExoMars Rover must send to the ROCC the Essential Data and the Critical Data, so that the Ground operators can plan the short term activities. The TGO has to pass over the RM at least twice a day, in overflights separated by 10/12 hours. The two passages are used as uplink of the TCs towards the Rover or as downlink of the TM from the Rover. Since the Satellite Relay is not sunsynchronous the overflights shift in the day, identifying two opposite situations regarding the Rover Working Time actually available:

- "Optimal" or "Morning-Evening" passages: the TM is downloaded to the ROCC during the Martian night, it is analysed, and the TCs are sent to the Rover before it wakes up. During the whole Theoretical Rover Working Time (i.e. when the solar arrays of the Rover provide enough energy to work) the Rover has time to run the downloaded AP.
- "Sub-optimal" or "Midnight-Midday" passages: the Rover has to interrupt the running AP in the middle of the Theoretical Rover Working Time to send the TM to the Ground. If, however, the Rover receives the TCs at midday, it only has less than half of the Theoretical Rover Working Time to perform the received AP.

The asynchronous condition of the TGO also has repercussions on the organization of the shifts on the Ground. Ideally, the Tactical Planning team members would receive the TM from the Rover, spend their shift analysing and planning the next SOL AP, and then send the TCs to the Rover before ending the shift.
Using this approach the ROCC Operators would work Mars time, i.e. synchronized to the TGO passes. In this case, to cover 24 hours, 7 days a week, they would need three shifts with a duration of 8 hours. Adding one hour of handover between the various teams, three 9 hours shifts are identified:

- Main Tactical shift: the beginning of the turn coincides with the arrival of the Rover TM to the ROCC. The TM is assessed, the AP is generated and uploaded with the TCs at the end of the shift.
- Consolidation Tactical shift: starting at the end of the eighth hour of the Main shift. In case of a third TGO overflight, the operators analyse and refine the AP generated in the previous shift and send the updated one to the TGO. Alternatively, they evaluate the downloaded TM in this further overflight.
- Optional Tactical shift: starting at the end of the eighth hour of the Consolidation shift, and ends with one hour overlapping with the Main shift. It can be used during the mission critical phases.

This approach increases the effectiveness of using available time between communication windows and maximizes time margins to overcome contingencies. On the other hand human factors have to be considered, and surely having every day shifts at different times worsens the physical and mental health of Ground operators.

In order to overcome this disadvantage the ROCC operators should work Earth time, considering always 9 hour shifts including an hour of handover:

- Morning shift: from 6 a.m. to 3 p.m.;
- Afternoon shift: from 2 p.m. to 11 p.m.;
- Night shift: from 10 p.m. to 7 a.m..

This would reduce mistakes due to human factors, but there would be serious problems in the circumstance that the shift handover occurs during critical activities.

3.2 General considerations about the shift scheduling approach

During the internship, an analysis has been performed in order to reproduce the Ground operator shift condition during the 2020 Exomars mission. An Excel workbook (*Shifts Scheduling at ROCC*) has been created to determine the feasibility of the two working approaches that can be used at the ROCC.

The main approach taken in account was the one synchronized to the TGO passes, based on the Mars time. The TGO overflight time has been taken from *Table 5-11 TGO support to the Rover Surface Mission* in [9].

The basic guidelines given in this document are:

- The TGO is the only data relay orbiter used.
- The study focuses on 221 SOLs: from 19th March 2021 (Landing SOL) to 31st October 2021.
- The Theoretical Rover Working Time is taken to be from 7:00 to 17:00 Mars time, when the solar arrays of the Rover provide enough energy to work.
- The displacement of the rover is negligible and its position coincides with the coordinates of Oxia Planum, the landing site: latitude of 18.159°N and longitude of 335.666°E.
- Only TGO passes longer than 2 minutes are taken into account.
- TGO overflights occurring before 12:00 Mars time are considered uplink passes, the others are considered downlink passes.

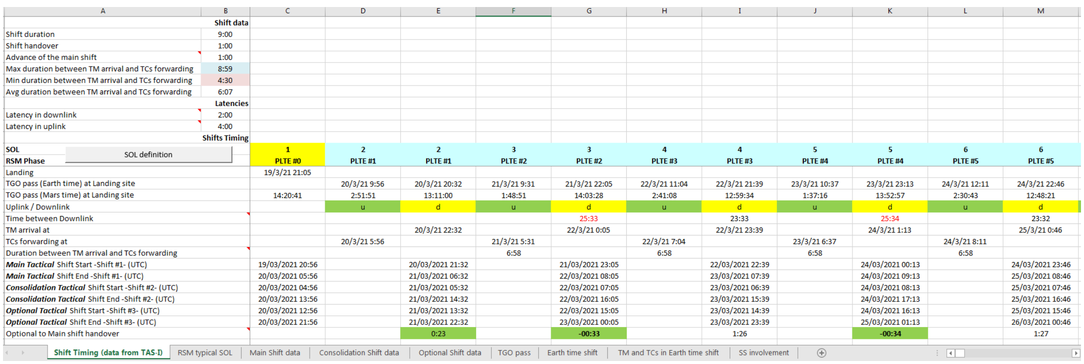
- In case of multiple morning passes, the Rover operations will start as soon as possible after the first uplink pass.
- In case of multiple overflights in the afternoon/evening, the operations should continue after the first downlink pass, in order to complete the AP.
- In case of more than 10 hours between the first and second pass in the SOL, the second one is considered as an uplink pass, even if it occurs in the afternoon/evening.

These guidelines let to decide if the predicted TGO pass will be used as uplink to, or downlink from, ExoMars Rover.

In the Excel file the user can find 9 worksheets:

- Shift Timing
- RSM typical SOL
- Main Shift data
- Consolidation Shift data
- Optional Shift data
- TGO pass
- Earth time shift
- TM and TCs in Earth time shift
- SS involvement

3.2.1 Shift Timing



A	B	C	D	E	F	G	H	I	J	K	L	M
	Shift data											
Shift duration	9:00											
Shift handover	1:00											
Advance of the main shift	1:00											
Max duration between TM arrival and TCs forwarding	8:59											
Min duration between TM arrival and TCs forwarding	4:30											
Avg duration between TM arrival and TCs forwarding	6:07											
	Latencies											
Latency in downlink	2:00											
Latency in uplink	4:00											
	Shifts Timing											
SOL	SOL definition	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
RSM Phase		**PLTE #0**	**PLTE #1**	**PLTE #1**	**PLTE #2**	**PLTE #2**	**PLTE #3**	**PLTE #3**	**PLTE #4**	**PLTE #4**	**PLTE #5**	**PLTE #5**
Landing		19/3/21 21:05										
TGO pass (Earth time) at Landing site			20/3/21 9:56	20/3/21 20:32	21/3/21 9:31	21/3/21 22:05	22/3/21 11:04	22/3/21 21:39	23/3/21 10:37	23/3/21 23:13	24/3/21 12:11	24/3/21 22:46
TGO pass (Mars time) at Landing site		14:20:41	2:51:51	13:11:00	1:48:51	14:03:28	2:41:08	12:59:34	1:37:16	13:52:57	2:30:43	12:48:21
Uplink / Downlink			u	d	u	d	u	d	u	d	u	d
Time between Downlink						25:33		23:33		25:34		23:32
TM arrival at				20/3/21 22:32		22/3/21 0:05		22/3/21 23:39		24/3/21 1:13		25/3/21 0:46
TCs forwarding at			20/3/21 5:56		21/3/21 5:31		22/3/21 7:04		23/3/21 6:37		24/3/21 8:11	
Duration between TM arrival and TCs forwarding					6:58		6:58		6:58		6:58	
Main Tactical Shift Start -Shift #1- (UTC)		19/03/2021 20:56		20/03/2021 21:32		21/03/2021 23:05		22/03/2021 22:39		24/03/2021 00:13		24/03/2021 23:46
Main Tactical Shift End -Shift #1- (UTC)		20/03/2021 05:56		21/03/2021 06:32		22/03/2021 08:05		23/03/2021 07:39		24/03/2021 09:13		25/03/2021 08:46
Consolidation Tactical Shift Start -Shift #2- (UTC)		20/03/2021 04:56		21/03/2021 05:32		22/03/2021 07:05		23/03/2021 06:39		24/03/2021 08:13		25/03/2021 07:46
Consolidation Tactical Shift End -Shift #2- (UTC)		20/03/2021 13:56		21/03/2021 14:32		22/03/2021 16:05		23/03/2021 15:39		24/03/2021 17:13		25/03/2021 16:46
Optional Tactical Shift Start -Shift #3- (UTC)		20/03/2021 12:56		21/03/2021 13:32		22/03/2021 15:05		23/03/2021 14:39		24/03/2021 16:13		25/03/2021 15:46
Optional Tactical Shift End -Shift #3- (UTC)		20/03/2021 21:56		21/03/2021 22:32		23/03/2021 00:05		23/03/2021 23:39		25/03/2021 01:13		26/03/2021 00:46
Optional to Main shift handover				0:23		-00:33		1:26		-00:34		1:27

Shift Timing (data from TAS-I) | RSM typical SOL | Main Shift data | Consolidation Shift data | Optional Shift data | TGO pass | Earth time shift | TM and TCs in Earth time shift | SS involvement

Figure 3.2: "Shift Timing" worksheet.

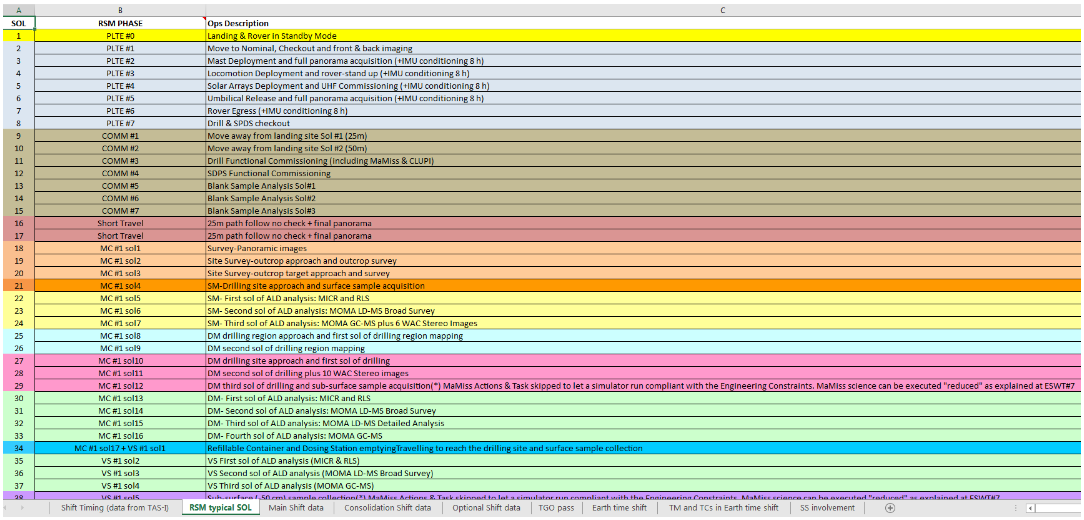
TGO pass in Mars time and in Earth time, and uplink/downlink pass direction allow definition of the start and the end shift timing, in an approach synchronized with the TGO passes.

In the "Shift Timing" worksheet (see Figure 3.2) the timetable of TM arrival at ROCC, and when TCs have to be forwarded to ESOC are defined. TM data are available at ROCC 2 hours after the afternoon/evening TGO overflight, introducing a latency in downlink of 2 hours on average. Such latency is due to the fact that a Ground station is not always avaiable to downlink data from TGO, or is eventually booked by other deep space missions. ESOC must receive TCs prepared by the ROCC some time in advance with respect to the morning TGO overflight and so we consider a 4 hours latency in uplink.
Having defined TM arrival in Earth time and TCs forwarding in Earth time, setting the Main Tactical Shift is straightforward. If the Main Shift starts 1 hours before the TM arrival at ROCC and shifts last 9 hours with an hour handover between shifts, Consolidation Shift and Optional Shifts start and end timing can be calculated as well.

The latencies, the handover duration, the begin of the main shift, and duration of each shift can be set in the "Shift Timing" sheet.

Given that the average duration between the TM arrival and the TCs forwarding is 6:07 hours, the Main Shift usually ends after the TCs forwarding, and there is no handover in the middle of the tactical planning process. So all preconfigured settings inserted in this sheet guarantee the nominal feasibility of the operations control in most cases.

3.2.2 RSM typical SOL



SOL	RSM PHASE	Ops Description
1	PLTE #0	Landing & Rover in Standby Mode
2	PLTE #1	Move to Nominal, Checkout and front & back imaging
3	PLTE #2	Mast Deployment and full panorama acquisition (+IMU conditioning 8 h)
4	PLTE #3	Locomotion Deployment and rover-stand up (+IMU conditioning 8 h)
5	PLTE #4	Solar Arrays Deployment and UHF Commissioning (+IMU conditioning 8 h)
6	PLTE #5	Umbilical Release and full panorama acquisition (+IMU conditioning 8 h)
7	PLTE #6	Rover Egress (+IMU conditioning 8 h)
8	PLTE #7	Drill & SPDS checkout
9	COMM #1	Move away from landing site Sol #1 (25m)
10	COMM #2	Move away from landing site Sol #2 (50m)
11	COMM #3	Drill Functional Commissioning (including MaMiss & CLUPI)
12	COMM #4	SDPS Functional Commissioning
13	COMM #5	Blank Sample Analysis Sol#1
14	COMM #6	Blank Sample Analysis Sol#2
15	COMM #7	Blank Sample Analysis Sol#3
16	Short Travel	25m path follow no check + final panorama
17	Short Travel	25m path follow no check + final panorama
18	MC #1 sol1	Survey-Panoramic images
19	MC #1 sol2	Site Survey-outcrop approach and outcrop survey
20	MC #1 sol3	Site Survey-outcrop target approach and survey
21	MC #1 sol4	SM-Drilling site approach and surface sample acquisition
22	MC #1 sol5	SM- First sol of ALD analysis: MICR and RLS
23	MC #1 sol6	SM- Second sol of ALD analysis: MOMA LD-MS Broad Survey
24	MC #1 sol7	SM- Third sol of ALD analysis: MOMA GC-MS plus 6 WAC Stereo Images
25	MC #1 sol8	DM drilling region approach and first sol of drilling region mapping
26	MC #1 sol9	DM second sol of drilling region mapping
27	MC #1 sol10	DM drilling site approach and first sol of drilling
28	MC #1 sol11	DM second sol of drilling plus 10 WAC Stereo images
29	MC #1 sol12	DM third sol of drilling and sub-surface sample acquisition(*) MaMiss Actions & Task skipped to let a simulator run compliant with the Engineering Constraints. MaMiss science can be executed "reduced" as explained at ESWT#7
30	MC #1 sol13	DM- First sol of ALD analysis: MICR and RLS
31	MC #1 sol14	DM- Second sol of ALD analysis: MOMA LD-MS Broad Survey
32	MC #1 sol15	DM- Third sol of ALD analysis: MOMA LD-MS Detailed Analysis
33	MC #1 sol16	DM- Fourth sol of ALD analysis: MOMA GC-MS
34	MC #1 sol17 + VS #1 sol1	Refillable Container and Dosing Station emptyingTravelling to reach the drilling site and surface sample collection
35	VS #1 sol2	VS First sol of ALD analysis (MICR & RLS)
36	VS #1 sol3	VS Second sol of ALD analysis (MOMA LD-MS Broad Survey)
37	VS #1 sol4	VS Third sol of ALD analysis (MOMA GC-MS)
38	VS #1 sol5	Sub-surface (-50 cm) sample collection(*) MaMiss Actions & Task skipped to let a simulator run compliant with the Engineering Constraints. MaMiss science can be executed "reduced" as explained at ESWT#7

Figure 3.3: "RSM typical SOL" worksheet.

The "RSM typical SOL" worksheet (see Figure 3.3) describes operations carried out during the RSM typical phase, corresponding to the SOL of the TGO overflight.
This worksheet is used by the Macro that renames SOLs in the other sheets. Pressing the `SOL definition` button, a typical phase of the mission is assigned to each SOL. This table is the result of the Strategic Planning of the RSM.

3.2.3 Main Shift data

Figure 3.4: "Main Shift data" worksheet.

In the "Main Shift data" worksheet (see Figure 3.4) all the most important data concerning the Main Tactical shift are summarized.

Some days the duration between TM arrival and TCs forwarding lasts less than 6 hours, which is the nominal period considered in preliminary studies for the tactical planning. This kind of contingency is highlighted with red text.
The minimum time interval detected is 4.5 hour, occurring at SOL 111. It is highlighted in pink.
The maximum time interval detected is 8 hours and 59 minutes, occurring at SOL 21. It is highlighted in blue. When more than 8 hours lapse between TM arrival and TCs forwarding, the Main Shift ends before the TCs forwarding. In this cases it is recommended that the start of the shift is delayed by at least 1 hour, in order to avoid the handover during the tactical planning process. This contingency occurs in SOL 21 and 51, and is highlighted in red.

The duration of the rest between two Main Shift have an average of 16.5 hours, with a minimum of 12 hours and 8 minutes, occurring at SOL 13, and is highlighted in turquoise, and a maximum of 40 hours and 9 minutes, occurring at SOL 59 and highlighted in orange. Every 30 days there is at least one 24 hours (or more) rest, in particular at SOL 10, 29, 56, 59, 88, 113, 118, 148, 163, 177, 207 and 217. They are highlighted in yellow. Every 30 SOLs on average (SOL 29, 59, 88, 118, 148, 177 and 207) resting periods are up to 40 hours long.

3.2.4 Consolidation Shift data

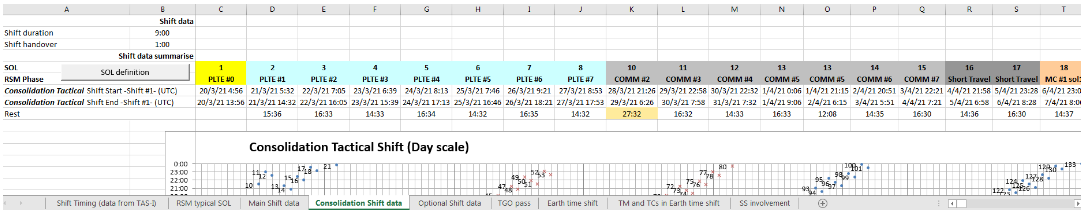


Figure 3.5: "Consolidation Shift data" worksheet.

In the "Consolidation Shift data" worksheet (see Figure 3.5) all the most important data concerning the Consolidation Tactical shift are summarized.

The Consolidation Shift lasts 9 hours and begins 1 hour before the end of the Main Shift. Therefore, the Consolidation Shift schedule, rests and considerations are dictated by the Main Shift schedule.

3.2.5 Optional Shift data

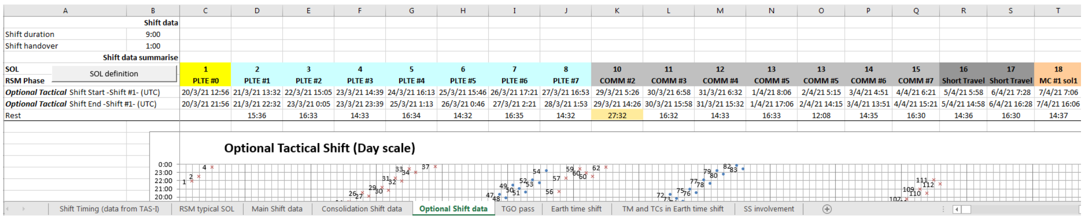


Figure 3.6: "Optional Shift data" worksheet.

In the "Optional Shift data" worksheet (see Figure 3.6) the most important data concerning the Optional Tactical shift are summarized.

Optional Shift lasts 9 hours and begins 1 hour before the end of the Consolidation Shift. Therefore, the Optional Shift schedule, rests and considerations are dictated by the Consolidation Shift schedule.

3.2.6 TGO pass

In the "TGO pass data" worksheet (see Figure 3.7) all the most important data concerning the TGO overflight on the landing site are summarized.

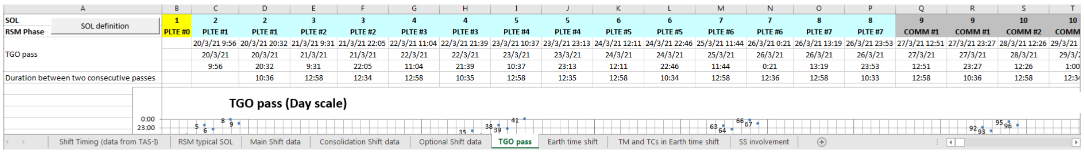


Figure 3.7: "TGO pass" worksheet.

Every 29 or 30 SOLs there are 25 hours and 36 minutes between passes, specifically at SOL 29, 59, 88, 118, 148, 177 and 207. This means that an overflight has been missed in the previous SOL. This almost exact periodicity of the missing pass is lost in shift schedules between long rests since the uplink/downlink direction has been given to each overflights.

3.2.7 Earth time shift

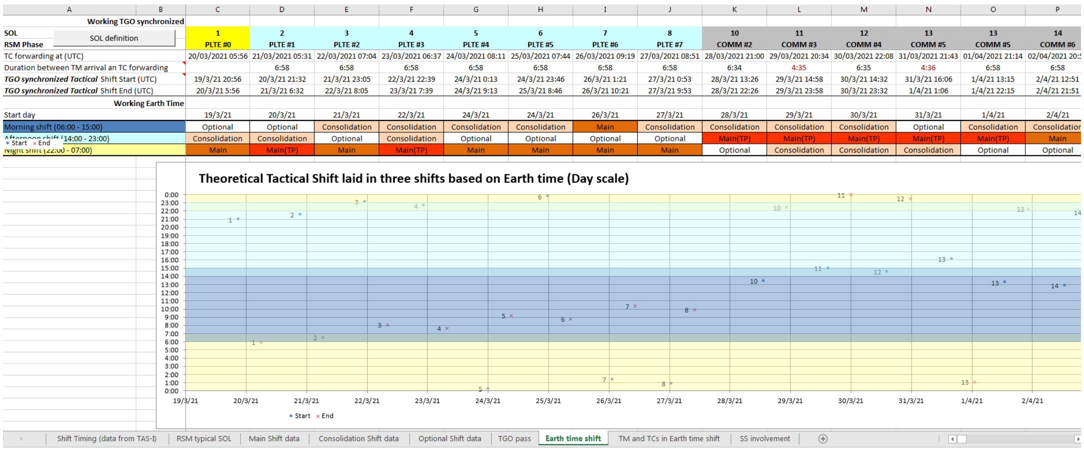


Figure 3.8: "Earth time shift" worksheet.

In order to work according to Earth time, it is important to identify the best two shifts which better fit with mission needs. This is done in "Earth time shift" worksheet (see Figure 3.8).

Once the three shifts (morning, afternoon and night) have been identified for a given day, it is possible to study when the TGO synchronized Main Tactical Shift is placed. It will then be possible to select the two most appropriate shifts. See Figure 3.9.

Considering definition similar to the TGO synchronized shift, we can prefer a Main Shift of the three in the day which maximizes its overlap with time between the TGO synchronized Main Shift start (1 hours before the TM arrival at ROCC) and the TGO synchronized Main Shift end (9 hours later). The Consolidation Shift contains the rest of the hours in the TGO synchronized Tactical Shift. The Optional shift does not contain hours belonging to the TGO synchronized Tactical Shift.

Figure 3.9: Theoretical Tactical Shift laid in three shifts based on Earth time.

For some SOLs the two shifts are easily chosen because most of the TGO synchronized Main Shift overlaps with the morning or the afternoon or the night Earth time shift, corresponding to the Main Earth time shift. The remaining part of the TGO synchronized Main Shift falls in the hours belonging to the previous or next Earth time shift, corresponding to the Consolidation Earth time shift. The third, unused, Earth time shift corresponds to the Optional Earth time shift, which occurs between the TCs forwarding and the TM arrival.
In best case scenarios, the TGO synchronized Main Shift coincides exactly with either the morning, afternoon, or night Earth time shift that corresponds to the Main Earth time shift. The others two Earth time shifts could be chosen as Consolidation Earth time shift. However, the tactical planning process will be executed in the Main Earth time shift selected. This is the case for SOL 4, 11, 12, 15, 33, 34, 37, 52, 59, 62, 77, 80, 95, 98, 99, 145, 146, 149, 171, 172, 174, 189, 192, 193, 207, 210, 211 and 218.
In the worst case scenario, the TGO synchronized Main Shift falls exactly in the middle of two Earth time -based shifts and their handover occurs in the middle of the tactical planning. In this case, in critical mission phase it is best to abandon the working Earth time approach, or consider TM arrival and TCs forwarding timing with respect to Earth time shift timing. The "TM and TCs in Earth time shifts" sheet was created to facilitate this step. This circumstance occurs at SOL 7, 22, 24, 25, 40, 42, 43, 44, 46, 65, 68, 69, 71, 86, 89, 90, 102, 105, 106, 107, 108, 115, 116, 118, 119, 134, 135, 136, 137, 140, 152, 153,

154, 155, 156, 158, 163, 165, 177, 178, 180, 181, 183, 196, 198, 199, 201, 202 and 214. In these SOLs, if TM arrival and TCs forwarding timing are detected in the same Earth time Shift, the Main Shift choice is straightforward, since tactical planning must be performed within this time frame. This fortuitous circumstance is highlighted in red (e.g. at SOL 2).

3.2.8 TM and TCs in Earth time shift

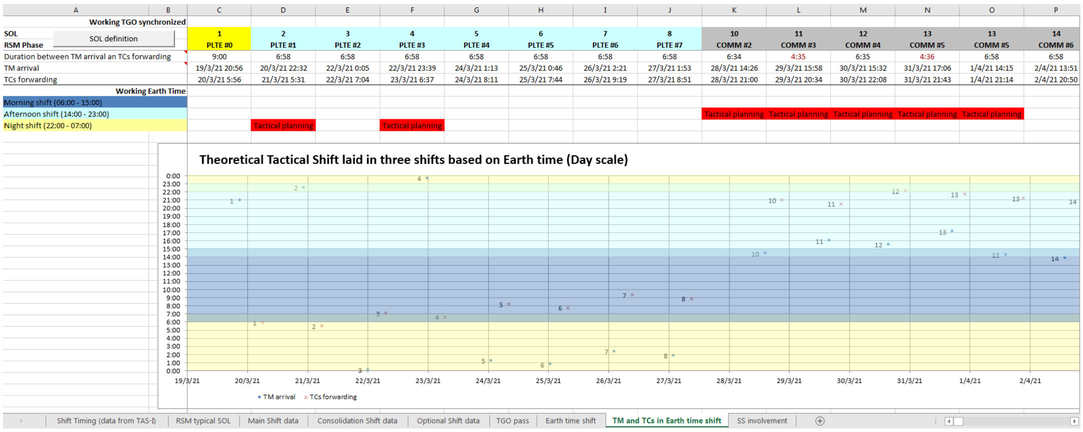


Figure 3.10: "TM and TCs in Earth time shift" worksheet.

"TM and TCs in Earth time shift" worksheet (see Figure 3.10) shows the graph where TM arrival and TCs forwarding timing are identified in the Earth time shifts.
In the best case scenario, both these times are contained in the same band, the worst case is when the two timings are symmetrical to the handover. The best situation is highlighted by a red fill.

3.2.9 SS involvement

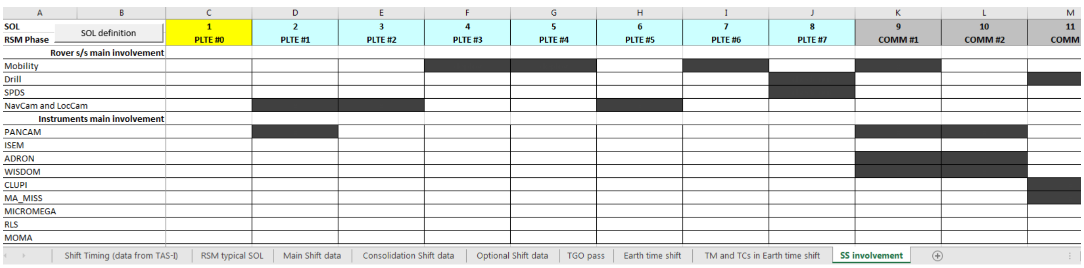
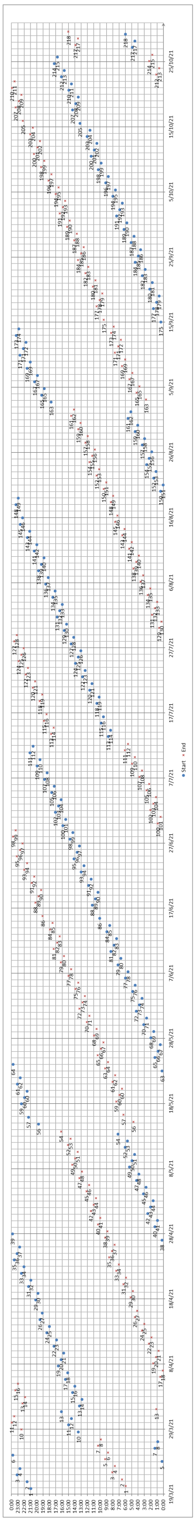
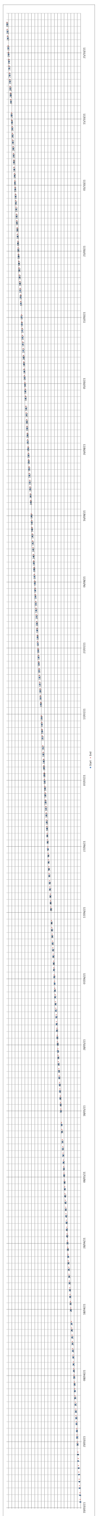


Figure 3.11: "SS involvement" worksheet.

Using [10] as reference, the subsystems and instruments involvement is summarized in the "SS involvement" worksheet (see Figure 3.11).

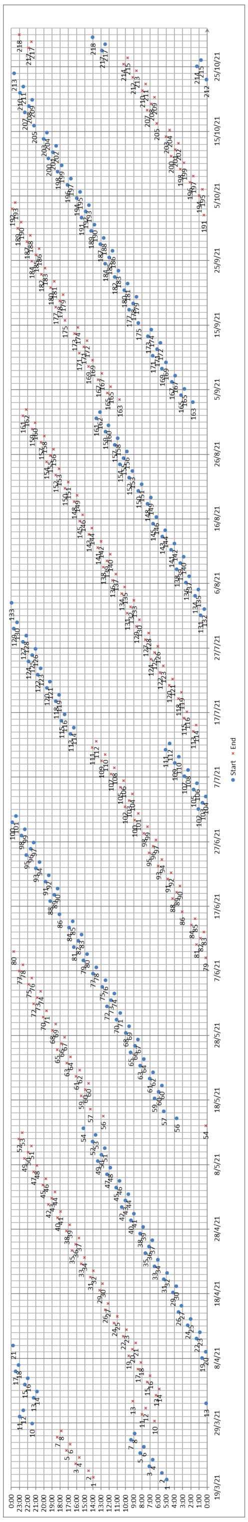


(a) Day scale.

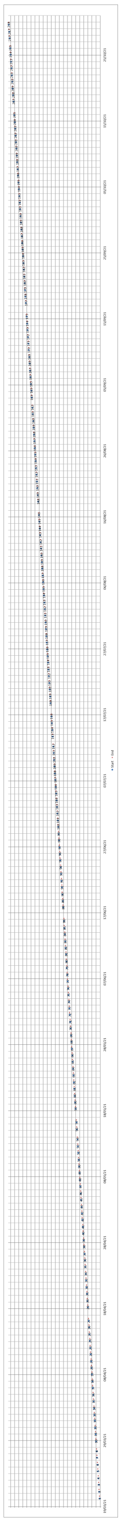


(b) Mission scale.

Figure 3.12: Main shift.

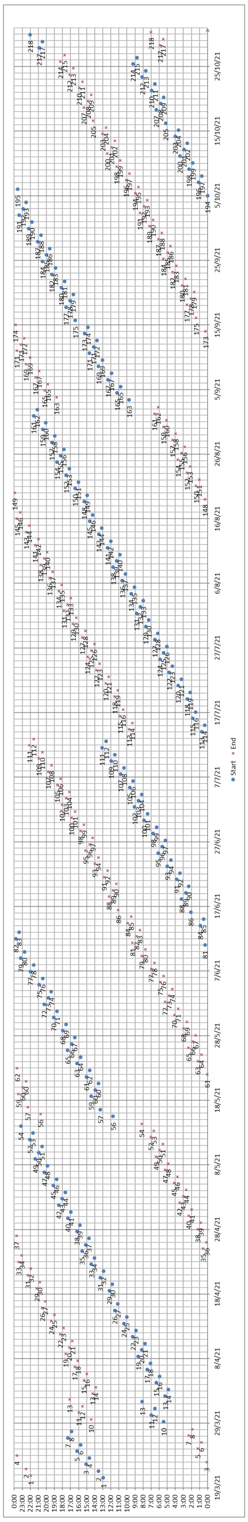


(a) Day scale.

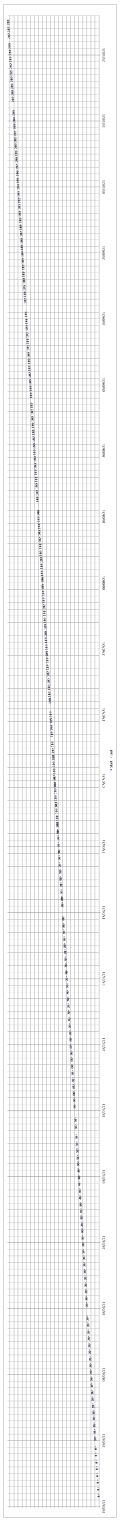


(b) Mission scale.

Figure 3.13: Consolidation shift.

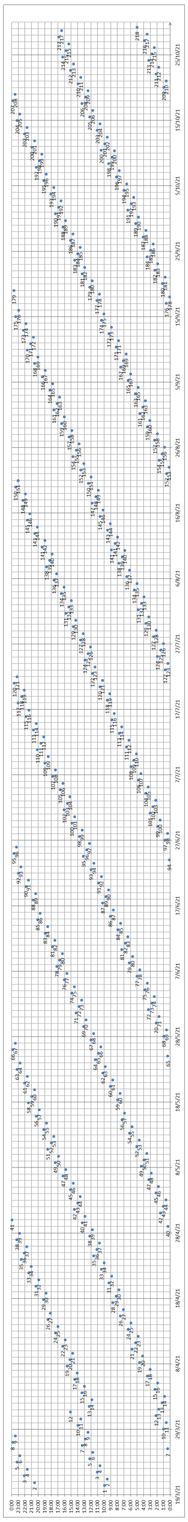


(a) Day scale.

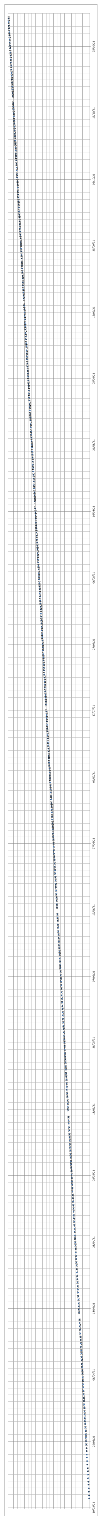


(b) Mission scale.

Figure 3.14: Optional shift.



(a) Day scale.



(b) Mission scale.

Figure 3.15: TGO overflight.

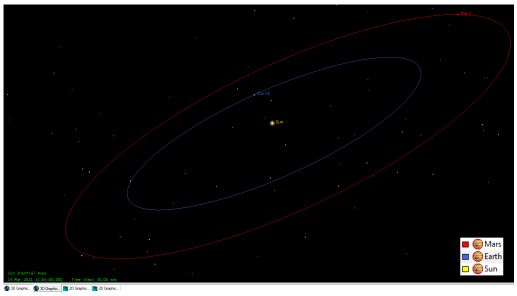
3.3 Shift scheduling at ROCC

Having performed analysis and drawn considerations on data from preliminary phases of mission planning, a more in-depth study was then carried out. In the following analysis the TGO overflights have been obtained with the STK simulator tool.

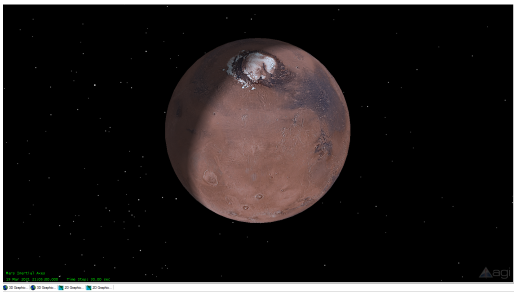
3.3.1 STK scenario creation, and TGO-RM communication simulation

The STK simulation tool allows the user to insert objects with specific characteristics in the Solar System and in the planets of interest: Mars and Earth.

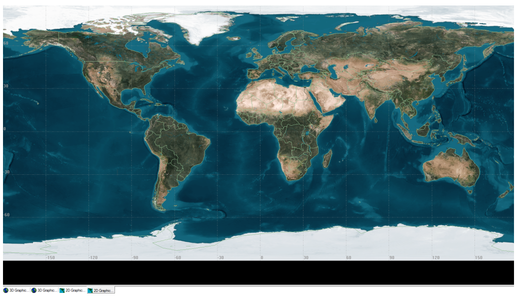
Figure 3.16 shows a 3D view of the Solar System (Fig. 3.16(a)) with selected planets, a 3D view of Mars (Fig. 3.16(b)) and a 2D view of the Earth (Fig. 3.16(c)) and Mars (Fig. 3.16(d)).



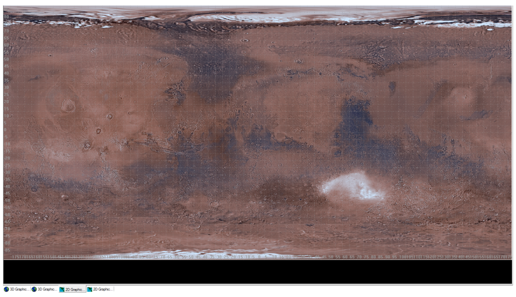
(a) Earth and Mars in the Solar System in a 3D view.



(b) Mars in a 3D view.



(c) Earth in a 2D view.



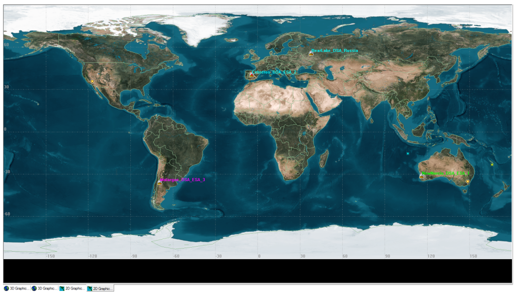
(d) Mars in a 2D view.

Figure 3.16: Empty scenario.

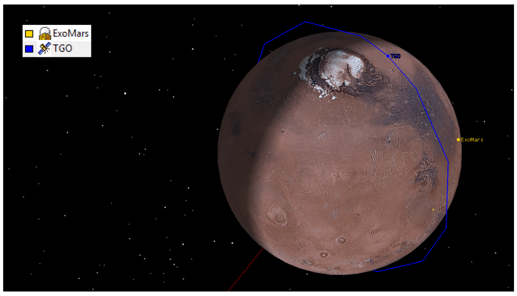
In order to create the scenario:

- The four DSAs acting as Ground Stations have been inserted on Earth, as shown in Figure 3.17(a).

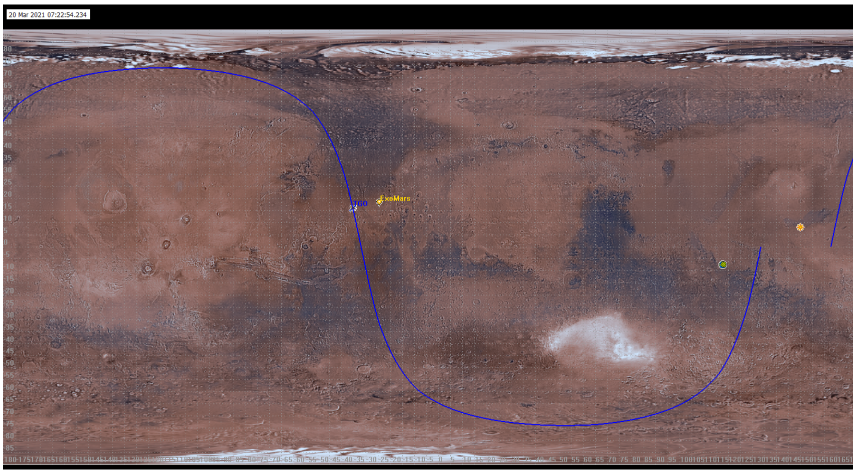
- The ExoMars Rover and the TGO satellite have been inserted on Mars, as shown in Figure 3.17(b). This scenario allows the analysis of the communication windows between the TGO and the RM, when the TGO overflights the Oxia Planum area, see Figure 3.17(c).



(a) Earth in a 2D view, with the four DSAs Ground Station highlighted.



(b) Mars in a 3D view, with the orbiting TGO and the RM placed in the Oxia Planum landing area.



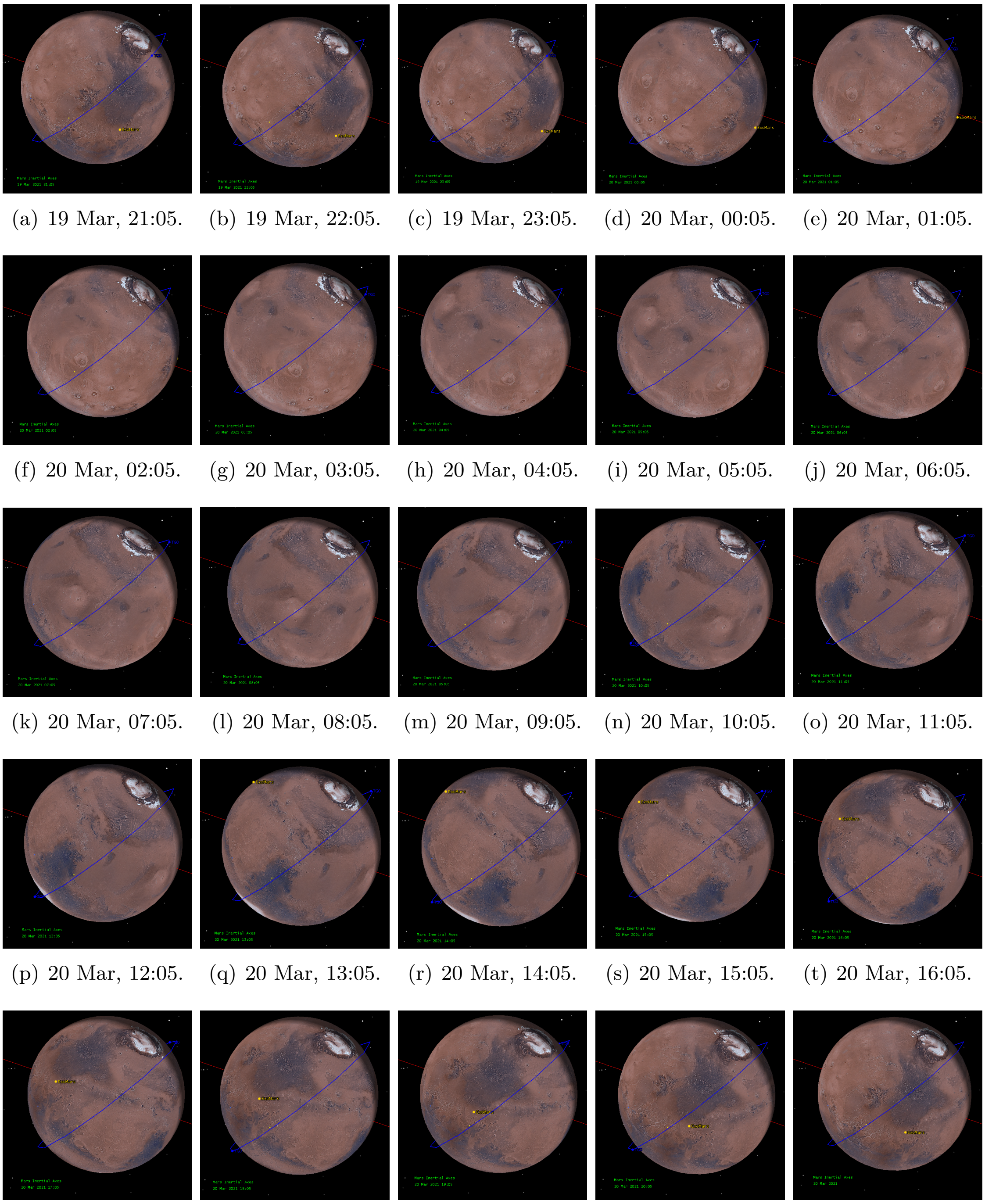
(c) Mars in a 2D view, with the orbit of the TGO projected on the ground and the RM placed in the Oxia Planum landing area.

Figure 3.17: Set scenario.

The Rover has been inserted as a *Facility* object, thus fixed, placed in the coordinates of the landing site. In this type of analysis, the RM movement from Oxia Planum is negligible. The propagation of the TGO orbit has been described through a *Spice Kernels Set*. This provides information on the position of the satellite in terms of time, coordinates and speed, taking into account the ephemeris of the spacecraft and of the Solar System bodies.

Figure 3.18 shows the first 24 hours of ExoMars Rover on the Martian soil, after landing on 19 March 2021 at 9:05 p.m..

Figure 3.19 shows ExoMars Rover on the Martian soil, after landing, and at one month



(a) 19 Mar, 21:05. (b) 19 Mar, 22:05. (c) 19 Mar, 23:05. (d) 20 Mar, 00:05. (e) 20 Mar, 01:05.

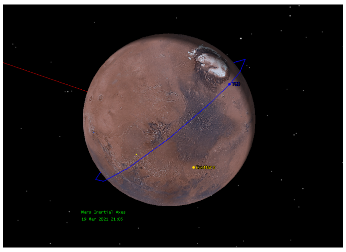
(f) 20 Mar, 02:05. (g) 20 Mar, 03:05. (h) 20 Mar, 04:05. (i) 20 Mar, 05:05. (j) 20 Mar, 06:05.

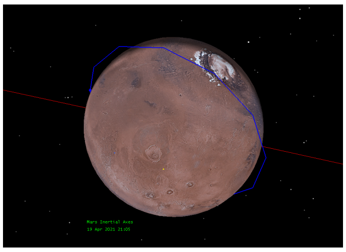
(k) 20 Mar, 07:05. (l) 20 Mar, 08:05. (m) 20 Mar, 09:05. (n) 20 Mar, 10:05. (o) 20 Mar, 11:05.

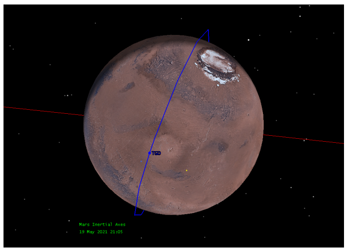
(p) 20 Mar, 12:05. (q) 20 Mar, 13:05. (r) 20 Mar, 14:05. (s) 20 Mar, 15:05. (t) 20 Mar, 16:05.

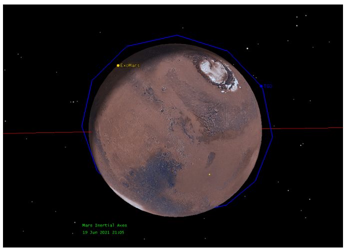
(u) 20 Mar, 17:05. (v) 20 Mar, 18:05. (w) 20 Mar, 19:05. (x) 20 Mar, 20:05. (y) 20 Mar, 21:05.

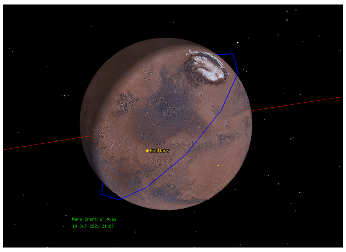
Figure 3.18: ExoMars Rover first day on Mars surface.

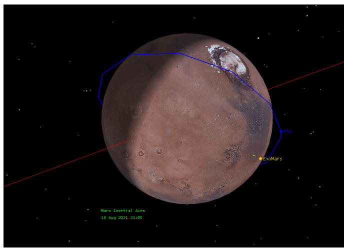

(a) 19 March 2021.

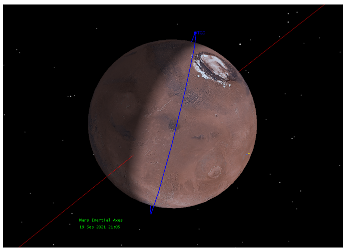

(b) 19 April 2021.


(c) 19 May 2021.


(d) 19 June 2021.


(e) 19 July 2021.


(f) 19 August 2021.


(g) 19 September 2021.

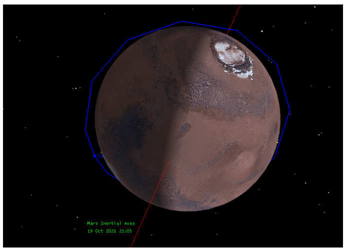

(h) 19 October 2021.

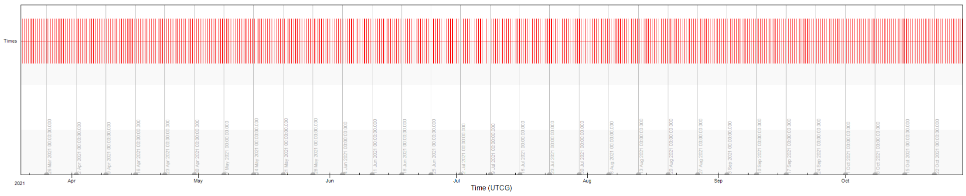
Figure 3.19: ExoMars Rover on Mars surface during the entire mission.

intervals until the end of the mission.

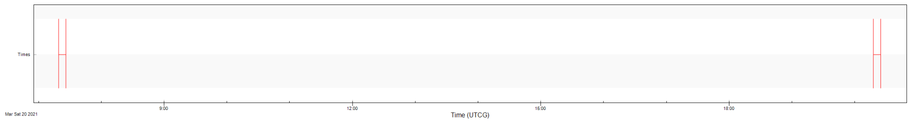
In Figures 3.17(c), 3.18 and 3.19 the TGO is represented as a blue dot on its orbit, and the Rover is a yellow dot fixed on the Martian surface. To the right of Figure 3.17(c) it is also possible to see the positions of the Sun (star-shaped sign) and the Earth (planet-shaped sign) projected onto the Martian soil. In Figures 3.18 and 3.19 the Earth and Sun are shown as yellow and blue dots, respectively.

Once the desired scenario has been created, the two objects whose communication has to be analysed are selected: in this case ExoMars Rover and TGO. Data and graphs are obtained with respect to the communication windows in Earth time (start time, stop time and duration of each access), and relative to azimuth, elevation and range of each communication window.

Figure 3.20 shows the graph of simulation results concerning the communication windows between TGO and RM, both throughout the entire mission (Fig. 3.20(a)), and the detail



(a) Mission scale.



(b) Day scale: Saturday 20 March 2021.

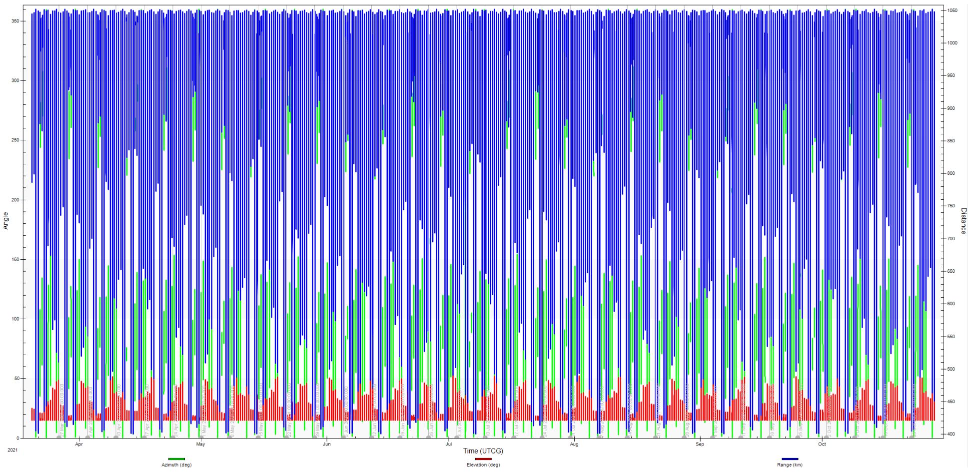
Figure 3.20: ExoMars Rover to Satellite TGO access times.

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
	1	20/03/2021 07:19:10	20/03/2021 07:26:22	431.446
	2	20/03/2021 20:17:36	20/03/2021 20:24:46	430.003
	3	21/03/2021 06:51:18	21/03/2021 07:01:32	613.410
	4	21/03/2021 19:49:28	21/03/2021 19:59:40	611.944
	5	22/03/2021 06:26:44	22/03/2021 06:32:48	363.732
	6	22/03/2021 08:28:04	22/03/2021 08:31:18	194.464
		⋮		
Global statistics				
Min Duration	59	14/04/2021 18:19:49	14/04/2021 18:20:45.135	55.432
Max Duration	246	7/07/2021 04:02:49	7/07/2021 04:13:03.131	614.021
Mean Duration				483.916
Total Duration				240506.257

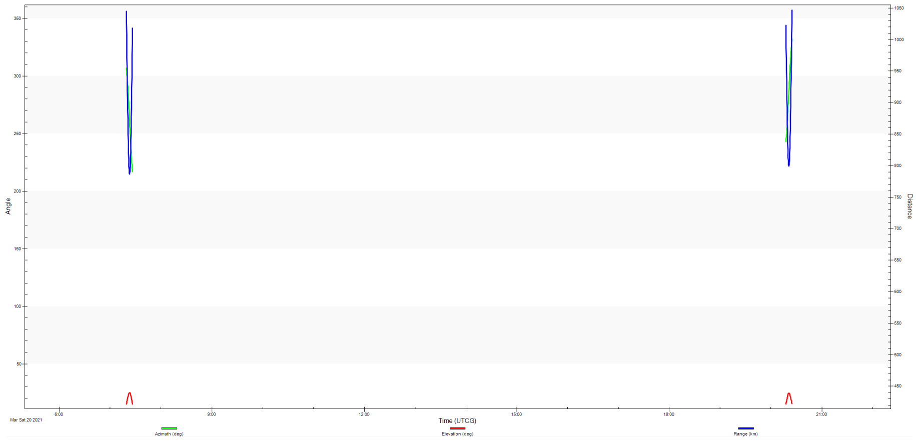
Table 3.1: ExoMars Rover to Satellite TGO access times.

of the first day of the mission (Fig. 3.20(b)). Table 3.1 reports a first part of the detected communication windows, as well as summary statistics about the entire mission.

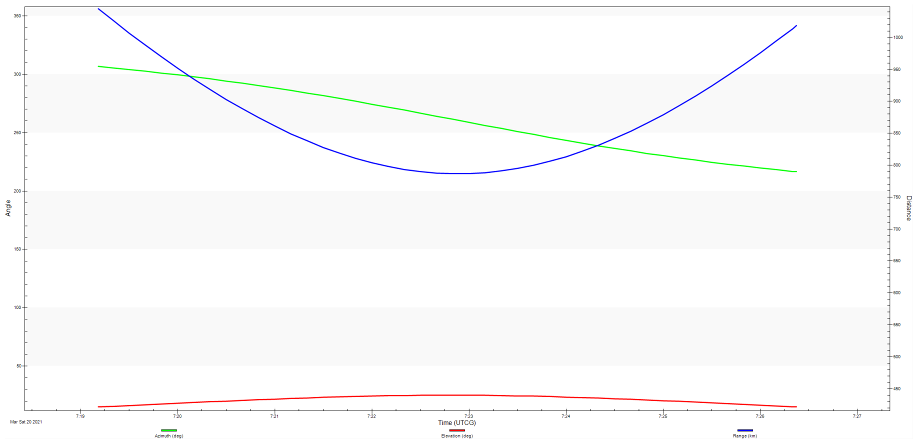
Figure 3.21 shows analysis results of each communication window with regard to the azimuth, elevation and range parameters, throughout the entire mission (Fig.3.21(a)), and in details for the first mission day (Fig. 3.21(b)), and for a single overflight (Fig. 3.21(c)). Table 3.2 reports the data related to the first day of the mission, as well as summary statistics of each pass and concerning the entire mission.



(a) Mission scale.



(b) Day scale: Saturday 20 March 2021.



(c) Single overflight: Saturday 20 March 2021 morning pass.

Figure 3.21: ExoMars Rover to Satellite TGO azimuth, elevation and range data.

	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
	20 Mar 2021 07:19:10	306.650	15.000	1044.787
	20 Mar 2021 07:20:10	297.763	18.754	934.851
	20 Mar 2021 07:21:10	286.118	22.222	849.074
	20 Mar 2021 07:22:10	271.846	24.548	797.932
	20 Mar 2021 07:23:10	256.117	24.880	788.342
	20 Mar 2021 07:24:10	241.039	23.040	821.784
	20 Mar 2021 07:25:10	228.267	19.718	893.350
	20 Mar 2021 07:26:10	218.215	15.814	994.670
	20 Mar 2021 07:26:22	216.459	15.000	1018.392
Section statistics				
Min Elevation	20 Mar 2021 07:26:22	216.459	15.000	1018.392
Max Elevation	20 Mar 2021 07:22:48	261.695	25.023	786.740
Mean Elevation			19.886	
Min Range	20 Mar 2021 07:22:53	260.558	25.017	786.625
Max Range	20 Mar 2021 07:19:10	306.650	15.000	1044.787
Mean Range				904.798
	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
	20 Mar 2021 20:17:36	242.763	15.000	1022.579
	20 Mar 2021 20:18:36	252.327	18.786	919.652
	20 Mar 2021 20:19:36	264.506	22.133	843.791
	20 Mar 2021 20:20:36	279.005	24.214	803.676
	20 Mar 2021 20:21:36	294.477	24.318	804.652
	20 Mar 2021 20:22:36	308.955	22.439	846.453
	20 Mar 2021 20:23:36	321.114	19.283	923.337
	20 Mar 2021 20:24:36	330.728	15.638	1027.176
	20 Mar 2021 20:24:46	332.155	15.000	1047.250
Section statistics				
		⋮		
		⋮		
Global statistics				
Min Elevation	24 Oct 2021 00:56:31	119.015	15.000	1023.189
Max Elevation	7 Jul 2021 04:08:01	77.874	89.689	401.394
Mean Elevation			27.335	
Min Range	7 Aug 2021 05:51:07	240.021	89.158	401.394
Max Range	21 Mar 2021 06:51:18	349.852	15.000	1052.080
Mean Range				809.069

Table 3.2: ExoMars Rover to Satellite TGO azimuth, elevation and range data.

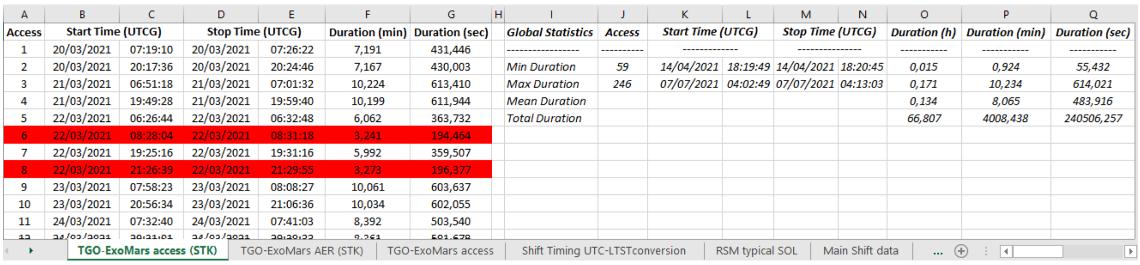
3.3.2 Excel workbook: *Shifts Scheduling at ROCC + STK*

An Excel workbook (*Shifts Scheduling at ROCC + STK*) has been created. In this new file it is possible to find the 9 worksheets with the same functionality as those found in the *Shifts Scheduling at ROCC* workbook described in Section 3.2, as well as three additional sheets that summarize the results of the STK tool simulation.:

- TGO-ExoMars access (STK)
- TGO-ExoMars AER (STK)
- TGO-ExoMars access
- Shift Timing UTC-LTSTconversion
- RSM typical SOL
- Main Shift data
- Consolidation Shift data
- Optional Shift data
- TGO pass
- Earth time shift
- TM and TCs in Earth time shift
- SS involvement

This workbook allows for Macros to be launched by pressing buttons in the sheets. The study analyzed in Section 3.2 becomes straightforward and all the considerations can be made by analyzing the cells that are highlighted by fills or special typesetting.

TGO-ExoMars access (STK)



Access	Start Time (UTCG)		Stop Time (UTCG)		Duration (min)	Duration (sec)
1	20/03/2021	07:19:10	20/03/2021	07:26:22	7,191	431,446
2	20/03/2021	20:17:36	20/03/2021	20:24:46	7,167	430,003
3	21/03/2021	06:51:18	21/03/2021	07:01:32	10,224	613,410
4	21/03/2021	19:49:28	21/03/2021	19:59:40	10,199	611,944
5	22/03/2021	06:26:44	22/03/2021	06:32:48	6,062	363,732
6	22/03/2021	08:28:04	22/03/2021	08:31:18	3,241	194,464
7	22/03/2021	19:25:16	22/03/2021	19:31:16	5,992	359,507
8	22/03/2021	21:26:39	22/03/2021	21:29:55	3,273	196,377
9	23/03/2021	07:58:23	23/03/2021	08:08:27	10,061	603,637
10	23/03/2021	20:56:34	23/03/2021	21:06:36	10,034	602,055
11	24/03/2021	07:32:40	24/03/2021	07:41:03	8,392	503,540

Global Statistics	Access	Start Time (UTCG)		Stop Time (UTCG)		Duration (h)	Duration (min)	Duration (sec)
----------------	----------	-------------		---------------		-----------	-----------	------------
Min Duration	59	14/04/2021	18:19:49	14/04/2021	18:20:45	0,015	0,924	55,432
Max Duration	246	07/07/2021	04:02:49	07/07/2021	04:13:03	0,171	10,234	614,021
Mean Duration						0,134	8,065	483,916
Total Duration						66,807	4008,438	240506,257

Figure 3.22: "TGO-ExoMars access (STK)" worksheet.

"TGO-ExoMars access (STK)" worksheet (see Figure 3.22) reports results of the communication between TGO and ExoMars Rover simulation, performed with the STK tool.

In this sheet it is possible to find the entire set of data of Table 3.1, and the calculation of the communication window duration in minutes. Also the statistics are reported. These are not used but may be interesting for those who interface with this file.

TGO-ExoMars AER (STK)

A	B	C	D	E	F	G	H	I	J	K	L
	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)		*Global Statistics*	*Time (UTCG)*	*Azimuth (deg)*	*Elevation (deg)*	*Range (km)*	
	------------------------	-------------	---------------	-----------		------------------	------------------------	-------------	---------------	-----------	
	20 Mar 2021 07:19:10.884	306.650	15.000	1044.787281		*Min Elevation*	*24 Oct 2021 00:56:31.624*	*119.015*	*15.000*	*1023.189890*	
	20 Mar 2021 07:20:10.000	297.763	18.754	934.851772		*Max Elevation*	*7 Jul 2021 04:08:01.752*	*77.874*	*89.689*	*401.394420*	
	20 Mar 2021 07:21:10.000	286.118	22.222	849.074440		*Mean Elevation*			*27.335*		
	20 Mar 2021 07:22:10.000	271.846	24.548	797.932216		*Min Range*	*7 Aug 2021 05:51:07.907*	*240.021*	*89.158*	*400.591896*	
	20 Mar 2021 07:23:10.000	256.117	24.880	788.342636		*Max Range*	*21 Mar 2021 06:51:18.909*	*349.852*	*15.000*	*1052.080286*	
	20 Mar 2021 07:24:10.000	241.039	23.040	821.784538		*Mean Range*				*809.069699*	
	20 Mar 2021 07:25:10.000	228.267	19.718	893.350901							
	20 Mar 2021 07:26:10.000	218.215	15.814	994.670636							
	20 Mar 2021 07:26:22.330	216.459	15.000	1018.392807							
Section Statistics											

Min Elevation	20 Mar 2021 07:26:22.330	216.459	15.000	1018.392892							
Max Elevation	20 Mar 2021 07:22:48.875	261.695	25.023	786.740758							
Mean Elevation			19.886								

TGO-ExoMars access (STK) | **TGO-ExoMars AER (STK)** | TGO-ExoMars access | Shift Timing UTC-LTSTconversion | RSM typical SOL | Main Shift data | ...

Figure 3.23: "TGO-ExoMars AER (STK)" worksheet.

"TGO-ExoMars AER (STK)" worksheet (see Figure 3.23) reports the results of the analysis on the Azimuth, Elevation and Range parameters of each TGO overflight.
In this sheet it is possible to find the entire set of data of Table 3.2, together with statistical information.

TGO-ExoMars access

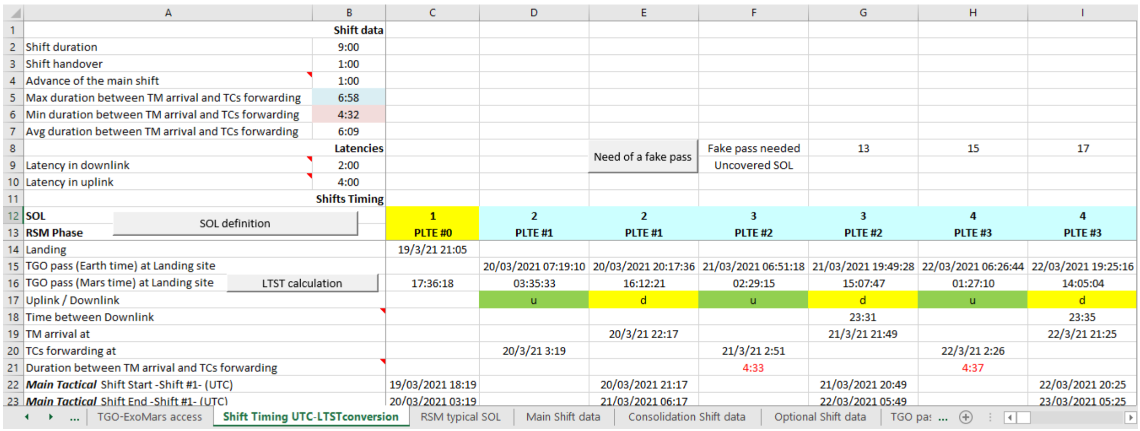
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Access	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Start Time (UTCG)	20/03/2021 07:19:10	20/03/2021 20:17:36	21/03/2021 06:51:18	21/03/2021 19:49:28	22/03/2021 06:26:44	22/03/2021 19:25:16	23/03/2021 07:58:23	23/03/2021 20:56:34	24/03/2021 07:32:40	24/03/2021 20:31:01	25/03/2021 09:05:44	25/03/2021 22:03:59	26/03/2021 08:39:07	26/03/2021 21:37:20	27/03/202 10:13:26
Stop Time (UTCG)	20/03/2021 07:26:22	20/03/2021 20:24:46	21/03/2021 07:01:32	21/03/2021 19:59:40	22/03/2021 06:32:48	22/03/2021 19:31:16	23/03/2021 08:08:27	23/03/2021 21:06:36	24/03/2021 07:41:03	24/03/2021 20:39:22	25/03/2021 09:15:02	25/03/2021 22:13:16	26/03/2021 08:48:44	26/03/2021 21:46:56	27/03/202 10:21:13
Duration (min)	7,191	7,167	10,224	10,199	6,062	5,992	10,061	10,034	8,392	8,361	9,310	9,282	9,622	9,601	7,788
Duration (sec)	431,446	430,003	613,410	611,944	363,732	359,507	603,637	602,055	503,540	501,678	558,578	556,939	577,336	576,080	467,271
Access selection															
Short Pass	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Start Time (UTCG)	22/03/2021 08:28:04	22/03/2021 21:26:39	05/04/2021 12:16:55	06/04/2021 01:15:36	12/04/2021 15:12:48	14/04/2021 18:19:49	15/04/2021 07:18:19	21/04/2021 21:13:00	22/04/2021 10:11:33	06/05/2021 01:02:19	06/05/2021 14:01:01	15/05/2021 07:04:23	15/05/2021 20:02:57	05/06/2021 13:47:45	06/06/202 02:46:30
Stop Time (UTCG)	22/03/2021 08:31:18	22/03/2021 21:29:55	05/04/2021 12:20:38	06/04/2021 01:19:10	12/04/2021 15:13:45	14/04/2021 18:20:45	15/04/2021 07:19:32	21/04/2021 21:16:42	22/04/2021 10:15:19	06/05/2021 01:05:31	06/05/2021 14:04:05	15/05/2021 07:06:29	15/05/2021 20:05:11	05/06/2021 13:50:21	06/06/202 02:48:53
Duration (min)	3,241	3,273	3,704	3,567	0,945	0,924	1,216	3,707	3,771	3,192	3,062	2,098	2,231	2,605	2,386
Duration (sec)	194,464	196,377	222,250	214,035	56,722	55,432	72,972	222,391	226,237	191,533	183,745	125,863	133,867	156,304	143,158

TGO-ExoMars access (STK) | TGO-ExoMars AER (STK) | **TGO-ExoMars access** | Shift Timing UTC-LTSTconversion | RSM typical SOL | Main Shift data | ...

Figure 3.24: "TGO-ExoMars access" worksheet.

"TGO-ExoMars access" worksheet (see Figure 3.24) identifies the communication windows between TGO and RM that can be used. It was decided to consider as *Short pass* all overflights that last less than 4 minutes. Short passes are not used because an acceptable amount of data could not be transferred. These overflights are detected, highlighted in red in the "TGO-ExoMars access (STK)" sheet, and they are excluded from the "Shift Timing UTC-LTSTconversion" sheet. The selection process is performed pressing the `Access selection` button.

Shift Timing UTC-LTST conversion



	A	B	C	D	E	F	G	H	I
1		**Shift data**							
2	Shift duration	9:00							
3	Shift handover	1:00							
4	Advance of the main shift	1:00							
5	Max duration between TM arrival and TCs forwarding	6:58							
6	Min duration between TM arrival and TCs forwarding	4:32							
7	Avg duration between TM arrival and TCs forwarding	6:09							
8		**Latencies**			Need of a fake pass	Fake pass needed	13	15	17
9	Latency in downlink	2:00				Uncovered SOL			
10	Latency in uplink	4:00							
11		**Shifts Timing**							
12	**SOL** SOL definition		**1**	**2**	**2**	**3**	**3**	**4**	**4**
13	**RSM Phase**		**PLTE #0**	**PLTE #1**	**PLTE #1**	**PLTE #2**	**PLTE #2**	**PLTE #3**	**PLTE #3**
14	Landing		19/3/21 21:05						
15	TGO pass (Earth time) at Landing site			20/03/2021 07:19:10	20/03/2021 20:17:36	21/03/2021 06:51:18	21/03/2021 19:49:28	22/03/2021 06:26:44	22/03/2021 19:25:16
16	TGO pass (Mars time) at Landing site LTST calculation		17:36:18	03:35:33	16:12:21	02:29:15	15:07:47	01:27:10	14:05:04
17	Uplink / Downlink			u	d	u	d	u	d
18	Time between Downlink						23:31		23:35
19	TM arrival at				20/3/21 22:17		21/3/21 21:49		22/3/21 21:25
20	TCs forwarding at			20/3/21 3:19		21/3/21 2:51		22/3/21 2:26	
21	Duration between TM arrival and TCs forwarding					4:33		4:37	
22	***Main Tactical*** Shift Start -Shift #1- (UTC)		19/03/2021 18:19		20/03/2021 21:17		21/03/2021 20:49		22/03/2021 20:25
23	***Main Tactical*** Shift End -Shift #1- (UTC)		20/03/2021 03:19		21/03/2021 06:17		22/03/2021 05:49		23/03/2021 05:25

Figure 3.25: "Shift Timing UTC-LTST conversion" worksheet.

The "Shift Timing UTC-LTST conversion" worksheet (see Figure 3.25) has the same functionality of the "Shift Timing" sheet described in Section 3.2.1. However, the TGO passes considered here are the ones selected in the "TGO-ExoMars access" sheet.

TGO overflights timing are expressed in Earth Time, but to decide if the pass is an uplink or a downlink it is mandatory to define the LTST (Local True Solar Time) on Mars. This operation is executed pressing the `LTST calculation` button. This button launches the Macro that converts an UTC Gregorian date (Year/Month/Day Hour:Minute:Second) in LTST at Oxia Planum landing site.

Most UTC-LTST conversion algorithms are based on the work of Michael Allison and Megan McEwen published in [2].

A Martian SOL is 3% longer than the solar day: the equivalent of 24 hours, 39 minutes and 35.244 seconds on Earth. In UTC-LTST conversion 24 parts/hours are identified in the SOL and the sexagesimal subdivision is applied, identifying 60 minutes in one hour and 60 seconds in one minute. Considering the eccentricity and the inclination of the planetary orbit which introduces a seasonal discrepancy, it is possible to calculate the time in LTST in an area at a specific longitude on Mars.

The step-by-step algorithm used in the worksheet is shown below:

STEP 1: The date and time expressed in Gregorian format are transformed into the JD_{ut}, the Julian date (decimal numeral) in universal time (UTC).

STEP 2: The JD_{tt}, the Julian date in Terrestrial Dynamical Time (TDT or TT), is calculated.

STEP 3: The Δt_{J2000}, the time offset from J2000 epoch (ie the number of days from 12:00 UT on January 1, 2000), is calculated.

STEP 4: The MSD (Mars SOL Date) referred to the Δt_{J2000} is calculated.

STEP 5: The MTC (Coordinated Mars Time), the respective UTC on Mars, is calculated.

STEP 6: The $LMST$ (Local Mean Solar Time) for a given longitude to Mars is calculated. In this case the longitude of Oxia Planum was provided.

STEP 7: It is determined the the EOT (Equation of Time) to calculate the $LTST$. The EOT depends on the Martian orbital parameters and the season in which they are calculated. It is the difference between True Solar Time and Mean Solar Time, and on Mars it can range from -51.1 min to $+39.9$ min.

As the result of this conversion, in the same Macro, each TGO overflight is labelled as uplink or as downlink pass. Overflights occurring before 12:00 Mars time are considered uplink passes, the others are considered downlink passes. If two consecutive passes are marked equal, the later one will be labelled with the other type.

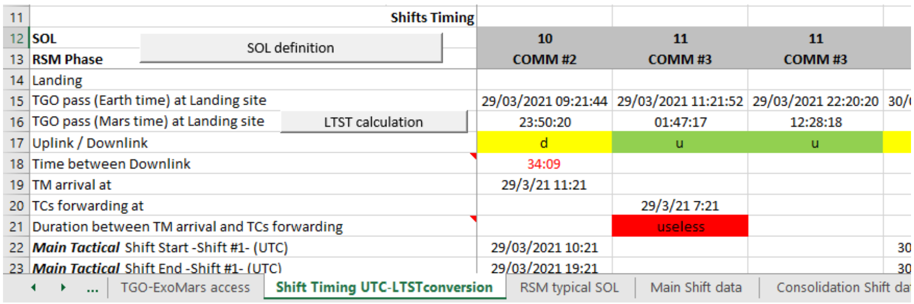
Once the direction of the pass is determined, it is straightforward to calculate the TM arrival at ROCC and the TCs forwarding timetable. Based on this schedule the Main, Consolidation and Optional tactical Shift timing is defined and printed from row 22 to row 27.

In this worksheet, pressing the `Need of a fake pass` button, it is possible to detect the day when there is only an overflight or when there are not any pass (uncovered SOL). In critical phases of the RSM ExoMars Rover and ROCC could be put in communication using substitute data relays. Currently the other orbiters taken into account are the NASA MRO and the NASA Maven.
The SOLs when a fake pass is needed are listed in a row from cell G9 onwards. Uncovered SOLs are collected and listed in a row from cell G10 onwards.

In the foremost rows of columns A and B it is possible to change setting data (e.g. latencies, handover durations). Average, maximum and minimum duration of the period between TM arrival and TCs forwarding are reported. In row 21 the maximum and the minimum duration are highlighted in pink and blue, respectively.

Red text in this worksheet highlights contingencies: less than the nominal 6 hours available for the tactical planning in row 21, day when three shifts do not cover the period between consecutive TCs forwarding in row 18. In this last case all the time available for the tactical planning is not exploited.

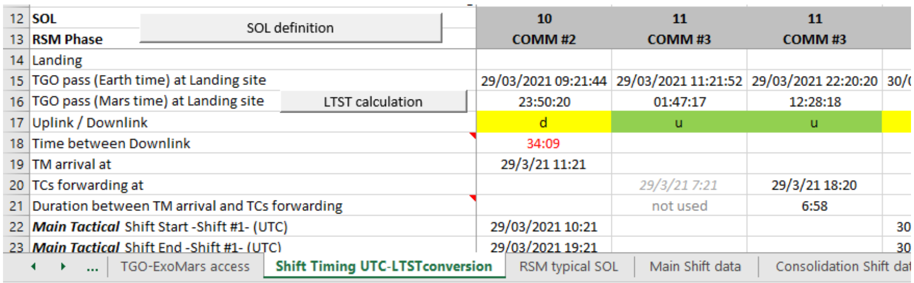
In row 21, it is possible to detect "useless" passes, highlighted in red, if TCs forwarding occur before the previous TM arrival. Figure 3.26(a) shows an example of this contingency being detected. Since this issue seldom appears, it is not necessary to devise an automatic



11		Shifts Timing				
12	**SOL**	SOL definition	**10**	**11**	**11**	
13	**RSM Phase**		**COMM #2**	**COMM #3**	**COMM #3**	
14	Landing					
15	TGO pass (Earth time) at Landing site		29/03/2021 09:21:44	29/03/2021 11:21:52	29/03/2021 22:20:20	30/(
16	TGO pass (Mars time) at Landing site	LTST calculation	23:50:20	01:47:17	12:28:18	
17	Uplink / Downlink		d	u	u	
18	Time between Downlink		34:09			
19	TM arrival at		29/3/21 11:21			
20	TCs forwarding at			29/3/21 7:21		
21	Duration between TM arrival and TCs forwarding			useless		
22	***Main Tactical*** Shift Start -Shift #1- (UTC)		29/03/2021 10:21			30
23	***Main Tactical*** Shift End -Shift #1- (UTC)		29/03/2021 19:21			30

... TGO-ExoMars access | **Shift Timing UTC-LTSTconversion** | RSM typical SOL | Main Shift data | Consolidation Shift da

(a) Contingency.



12	**SOL**	SOL definition	**10**	**11**	**11**	
13	**RSM Phase**		**COMM #2**	**COMM #3**	**COMM #3**	
14	Landing					
15	TGO pass (Earth time) at Landing site		29/03/2021 09:21:44	29/03/2021 11:21:52	29/03/2021 22:20:20	30/(
16	TGO pass (Mars time) at Landing site	LTST calculation	23:50:20	01:47:17	12:28:18	
17	Uplink / Downlink		d	u	u	
18	Time between Downlink		34:09			
19	TM arrival at		29/3/21 11:21			
20	TCs forwarding at			*29/3/21 7:21*	29/3/21 18:20	
21	Duration between TM arrival and TCs forwarding			not used	6:58	
22	***Main Tactical*** Shift Start -Shift #1- (UTC)		29/03/2021 10:21			30
23	***Main Tactical*** Shift End -Shift #1- (UTC)		29/03/2021 19:21			30

... TGO-ExoMars access | **Shift Timing UTC-LTSTconversion** | RSM typical SOL | Main Shift data | Consolidation Shift dat

(b) Solution.

Figure 3.26: "Shift Timing UTC-LTST conversion" worksheet contingency example.

solution. In this case the contingency appears at SOL 11, and it is possible to exploit the following pass, which occurs in early Mars afternoon, for the TCs uplink to the RM.

RSM typical SOL

The "RSM typical SOL" worksheet is identical to the one described in Section 3.2.2 (refer to Figure 3.3).
This worksheet is used by the Macro that renames SOLs in the other sheets, pressing the `SOL definition` button.

Main Shift data

The "Main Shift data" worksheet is identical to the one described in Section 3.2.3 (refer to Figure 3.4).

Pressing the `Calculate Shift data summarise` button all the Main Shift times are selected from the "Shift Timing UTC-LTST conversion" worksheet and repeat in this one. Day-scaled and mission-scaled graphs are created, to summarize the Ground operator schedule for the Main tactical shift.

At row 8 the rest duration is calculated and a day of break is highlighted in yellow (rest lasts more than 24 hours). Average, maximum and minimum duration of the rest are reported in this worksheet. Maximum and minimum duration are highlighted in orange and turquoise, respectively.

Row 5 cells with red text flag that less than 6 hours are available for the tactical planning.

Row 6 red cells signalize that the Main Shift ends before the TCs forwarding. Therefore it is recommended to delay the shift start by at least one hour.

Consolidation Shift data

The "Consolidation Shift data" worksheet is identical to the one described in Section 3.2.4 (refer to Figure 3.5). Day-scaled and mission-scaled graphs are created, to visualize the Ground operator schedule for the Consolidation tactical shift.

The Consolidation Shift schedule is straightforward calculated from the Main Shift schedule.

Optional Shift data

The "Optional Shift data" worksheet is identical to the one described in Section 3.2.5 (refer to Figure 3.6). Day-scaled and mission-scaled graphs are created, to visualize the Ground operator schedule for the Optional tactical shift.

The Optional Shift schedule is straightforward calculated from the Main and the Consolidation Shift schedule.

TGO pass

The "TGO pass" worksheet is identical to the one described in Section 3.2.6 (refer to Figure 3.7).

Day-scaled and mission-scaled graphs are created, and the duration of the period between two consecutive passes is determined.

Earth time shift

The "Earth time shift" worksheet is identical to the one described in Section 3.2.7 (refer to Figure 3.8).

In this worksheet the two Earth time -based shifts are chosen. It is then possible to label them as Main Earth time -based shift or as Consolidation Earth time -based shift. The Main shift is highlighted in orange, the Consolidation shift in light-orange. A red fill communicates that all the tactical planning is contained in one Earth time -based shift. This best case scenario occurs when TM arrival and TCs forwarding are in the same shift.

TM and TCs in Earth time shift

The "TM and TCs in Earth time shift" worksheet is identical to the one described in Section 3.2.8 (refer to Figure 3.10).

This worksheet is used to detect the circumstance in which TM arrival and TCs forwarding are in the same Earth time -based shift. Afterwards, the respective shift, which will contain all the tactical planning, is highlighted in the "Earth time shift" worksheet with red fill.

SS involvement

The "SS involvement" worksheet is identical to the one described in Section 3.2.9 (refer to Figure 3.11).

Chapter 4

Test set-up and equipment

Test campaigns in the Mars Terrain Simulator (MTS) based in ALTEC, contribute to confirm the adequacy of tools available at ROCC. Additionally, interactions between engineers and scientific teams leading the ExoMars Rover management during the mission, can be rehearsed during these tests.

The MTS facility is one of the most advanced in performing functional testing, because it is designed to reproduce the Mars surface, both morphologically and mineralogically.

The test campaigns described in Chapter 5 and executed during the internship, made use of the ExoTeR robotic platform, provided to ALTEC by ESA. This robotic platform mitigates the late availability of the Ground Test Model (GTM) in the project. ExoTeR was supplied together with its Landing Platform (LP) mock-up.

Figure 4.1: ExoTeR in the MTS Main Arena, with reduced light condition (Credit: ALTEC).

Figure 4.1 shows a picture of ExoTeR in the MTS Main Arena, during a test in sunset light condition.

3DROCS is the main software used during tests. It allows the user to control ExoTeR and the LP, uploading and running single command or APs in RAPD Language. During a 3DROCS on-line session it is possible to command and monitor the rover while it performs a test. On-line sessions are dedicated to MTS operators, e.g. people working on the field, checking and monitoring Rover activities in real-time. During a 3DROCS off-line sessions, the last on-line session recorded TM is injected as input. Off-line sessions are dedicated to Ground operators in training, allowing them to analyse the TM and re-run the activities as executed, in a 3D scenario.

4.1 The facility: the MTS and the ROCC Operation room

The MTS and the ROCC Operation Room are part of the wider ROCC system.
The MTS is the main simulation tool available to scientists and engineers to test the ExoMars Rover operations with a GTM. It recreates as accurately as possible the Mars surface environment and it aims at testing in stable and reproducible conditions.
The ROCC Operation room hosts the operational teams and their equipment for analysis, planning, monitoring of the Rover mission and, in this case, of Rover tests.

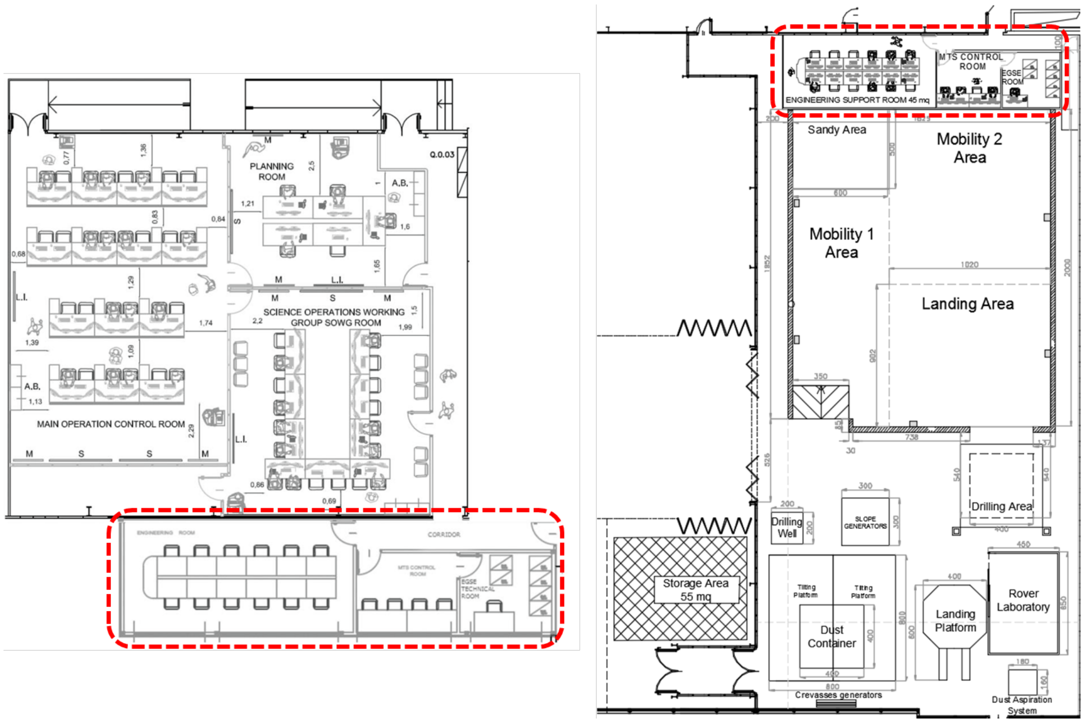


Figure 4.2: ROCC system located in ALTEC (Credit: ALTEC)

Figure 4.2 shows the floor plan of the ROCC system located at the ground floor of ALTEC.

The red line marks the common rooms between the two areas of planning and simulation.

In the floor plan on the left of the Figure, rooms that host engineering and scientific planning teams are displayed:

- The Main Operations Control room, hosting all the main operators involved in the tactical planning.
- The Planning room, mainly devoted to long and short -term strategic operations.
- The Science Operations Working Group room, where the AP for the following two SOLs will be created with the cooperation of scientific teams.

The floor plan on the right of the Figure shows the MTS facility. It consists of the Arena and the Equipment Area, where all the support equipment is stored.

In both floor plans there are the following three rooms, from where direct view on the MTS Arena is possible:

- The Rover Engineering Support room, which temporally hosts engineering teams in support of specific activities, or issued in case of complex troubleshooting activities require simulations.
- The Mars Terrain Simulator Control room, containing all the HW and SW equipment needed to monitor and command the MTS and the GTM.
- The MTS EGSE Technical room, hosting the Electrical Ground Support Equipments supplied with the GTM.

4.1.1 The MTS Arena

The MTS Arena simulates the characteristics of the Martian surface, and is composed by two main parts (see Figure 4.3):

- the Main Arena, hosting the Sandy, Mobility and Landing Areas;
- the Drilling Area, hosting the Drilling Facility and the Illumination Facility.

The Main Arena

The MTS Main Arena where all the test campaigns described in Chapter 5 have been executed, is a 20×16 meters zone covered with two different type of soil, see Figure 4.4.
The Sandy Area, with the Rhein Quartz Phyllosilicates (a very fine, white sand), is used to test the GTM slippage in unstable terrains. The Mobility and the Landing Areas, with the Pozzolana Volcanic Tuff (a silty orange sand), are used to test the locomotion and to simulate the Egress from the Lander mock-up, respectively.
Opaque curtains, with images from Mars, are mounted all around the Main Arena to avoid, as much as possible, the light reflections from the structure.

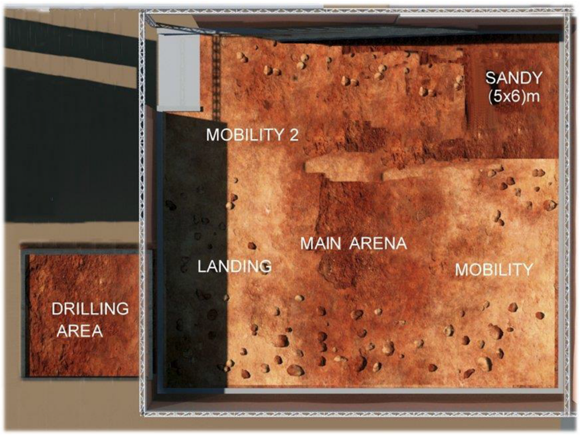


Figure 4.3: The MTS Arena depicted (Credit: ALTEC.)

Figure 4.4: The MTS Main Arena (Credit: ALTEC).

(a) Tilting Platform inclined at 30°. (b) Rocks in the Main Arena. (c) Crevasse of 15 *cm* depth. (d) Slope of 10°.

Figure 4.5: Terrain reconfiguration (Credit: ALTEC).

In the Landing Area it is possible to place the Tilting Platform, see Figure 4.5(a). It is an 8×8 meters inclinable platform used to test Egress and climbing procedures, setting the LP at different slope.

In the Mobility Area it is possible to reconfigure the terrain to replicate scenarios which the Rover will face on Mars. The principal equipment used are stones of varied dimensions, and slope and crevasse generators to create different rock distributions (see Figure 4.5(b)), rifts in the terrain (see Figure 4.5(c)) and hills (see Figure 4.5(d)).

The illumination system dedicated to the Main Arena consists of 40 LEDs mounted on the gantry, the metallic structure surrounding the Main Arena. It is possible to turn on/off

each side of the Arena independently to create low-light scenarios. Additionally, a movable light system can be used to create shadows inside the Arena.
Figure 4.6 shows a sunset scenario recreated in the MTS Main Arena.

Figure 4.6: Sunset in the MTS (Credit: ALTEC).

The Drilling Area

The Drilling area hosts two facilities: the Drilling Facility and the Illumination Facility, see Figure 4.7.

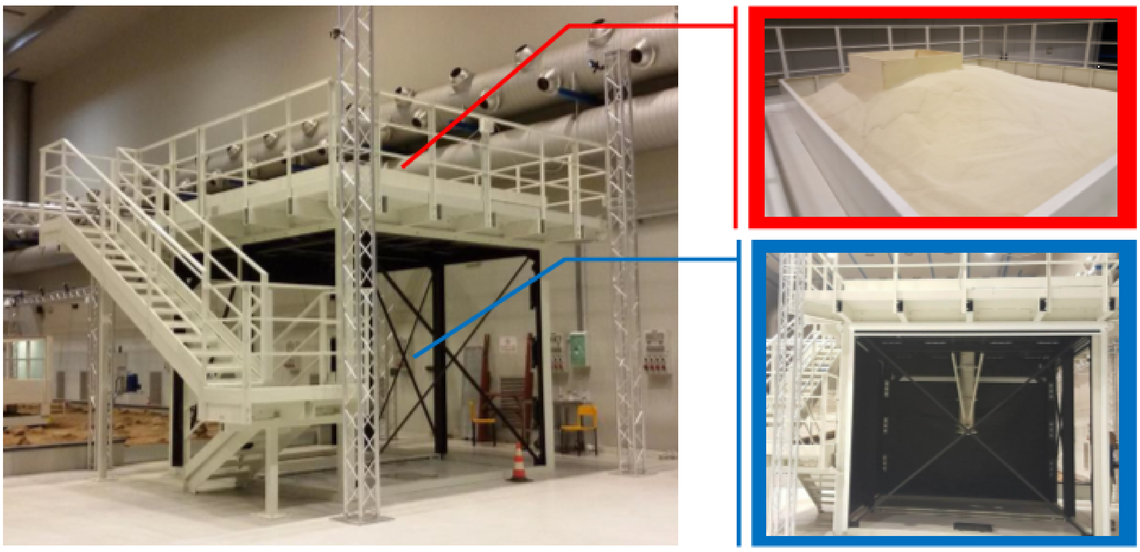


Figure 4.7: The Drilling Area: the Sand Box of the Drilling Facility highlighted in red, the Illumination Facility, with the Drilling Well mounted, highlighted in blue (Credit: ALTEC).

The Drilling Facility is used to test the GTM drilling operation, and allows testing this Rover ability at slopes up to 10°. In the Sand Box that supports the GTM there is a hole to which the Drilling Well can be fixed. It is a 2.1 m long cylinder that can be filled with layers of materials with different consistency and hardness, so that the GTM can test the drilling that it will perform during the mission. The Drilling Well can be tilted to adjust to the slope created in the Sand Box and can be removed when not in use, especially when the Illumination Facility is in use.

The Illumination Facility is placed at the bottom of the structure. It tests light effects on the Rover and simulates the intensity and temperature of the illumination on Mars. 28 dimmable LED lamps can be managed at once or in separate groups to create any desired lighting scenario. 2 light intensity sensors can move and reach any Illumination Facility point. These sensors can monitor the lux and color temperature parameters. Their measurements are used to adjust the light using the assigned software. The lamps provide a color temperature between 4000 and 4500°K and a light intensity up to 8000 lx, which can be dimmed in steps of 1% or 25% of its maximum value. To avoid unwanted reflections and light sources, the Illumination Facility is isolated using black curtains.

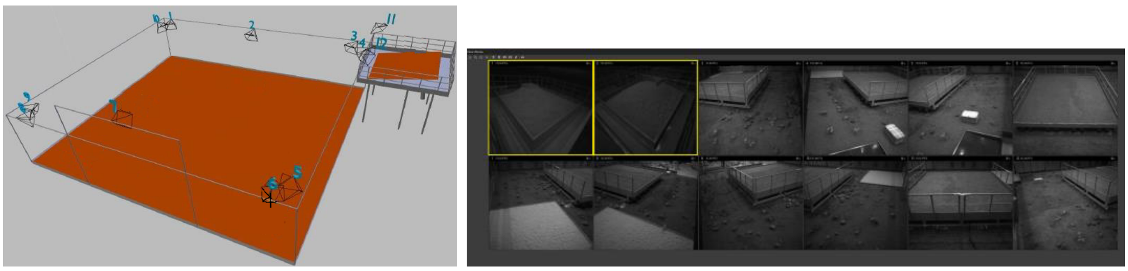
The Arena Systems

The MTS arena is equipped with different optic systems used to support tests. These specific instrument are called the Arena Systems.

The Arena Systems are classified as:

- Measurement System, to track the GTM motion inside the Arena;
- Modelling System, to generate the Digital Elevation Model (DEM) of the Arena;
- Ambient System, to acquire images and record the tests performed inside the Arena.

The Arena Systems cameras are placed all over the gantry.



(a) The 12 OptiTrack infrared cameras placed in the Arena.

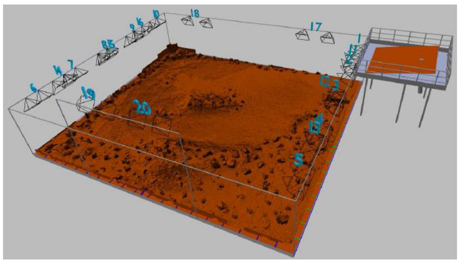
(b) The Measurement System cameras field of view, the yellow rectangles mark the Drilling Facility cameras.

Figure 4.8: The Measurement System (Credit: ALTEC).

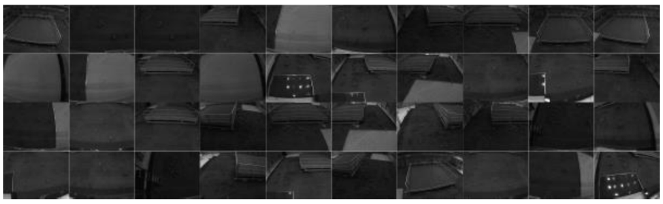
The Measurement System, see Figure 4.8, is composed of 12 OptiTrack infrared cameras.

The Measurement System has two cameras dedicated to track movements inside the Drilling Facility. These two cameras are tethered to a structure independent of the Drilling Facility, in order to prevent vibrations caused by on-going tests.

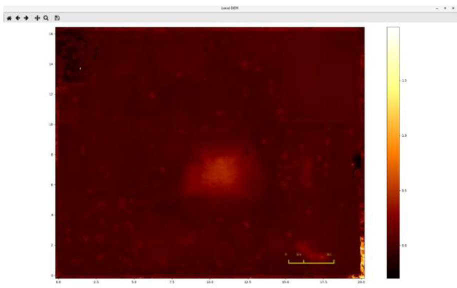
OptiTrack cameras detect reflective markers. Making use of the Motive:Tracker (a tool from OptiTrack), it is possible to group individual markers into rigid bodies. This system tracks in real-time a moving object in the Main Arena and in the Drilling Facility with an accuracy of 4 mm and 1°.
AS4MTS is a SW developed specifically for the MTS purposes by the DEL/Aberystwyth University. It uses information provided by Motive:Tracker, allowing the user to track a specific object or individual markers, to log and to save body poses in terms of xyz coordinates and yaw, pitch, roll angles.



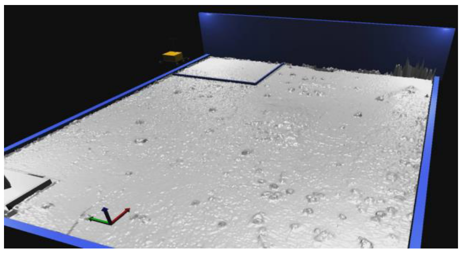
(a) The 20 pairs of Modelling System cameras placed onto the Main Arena graint.



(b) The Modelling System cameras field of view.



(c) The 2D visualization of MTS DEM.



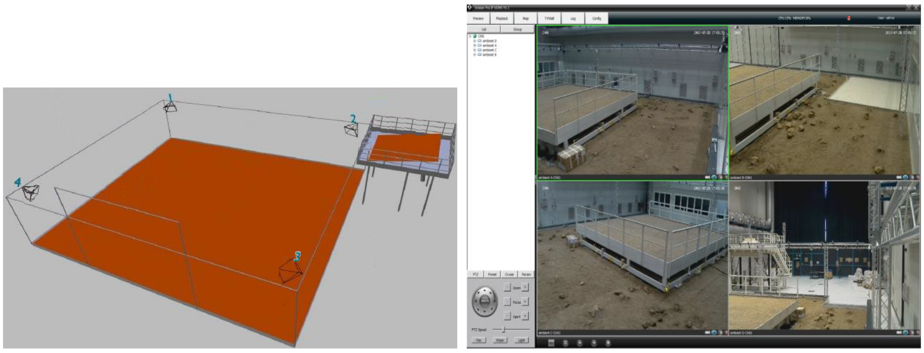
(d) The 3D visualization of MTS DEM.

Figure 4.9: The Modelling System (Credit: ALTEC).

The Modelling System, see Figure 4.9, is composed of 20 pairs of digital cameras.
The images of these camera pairs are processed with stereo-algorithms to generate the DEM of the Main Arena. The point cloud identified by each individual camera can generate a 2D image. Knowing the positions of the two cameras that point at the same place on the ground, the position of each point is identified in the Arena coordinate system, using the two point clouds (the stereocopia), through the algorithm. In this way the 3D image, i.e. the DEM, is created.

With AS4MTS, in addition to acquiring and displaying the Local DEM of the Main Arena, it is possible to load and display the Mission DEM generated by the ExoMars Rover, and to create a "Heatmap". The latter is calculated by highlighting the differences between the Mission DEM and the Local DEM, and allows the MTS user to faithfully replicate the scenario that the RM is facing on Mars in case of contingency.

The display mode of these DEMs can be 2D or 3D. In a 3D visualization it is possible to project the real-time movement of the GTM inside the Arena.



(a) The 4 Ambient cameras placed in the Main Arena.

(b) The Ambient System cameras field of view.

Figure 4.10: The Ambient System (Credit: ALTEC).

The Ambient System is composed of 4 security cameras positioned at the corners of the Main Arena gantry, see Figure 4.10.
The images acquired by these cameras are used for public relations and training purposes.

4.1.2 The ROCC Operation Room

Test in blind-mode requires TM data assessment to be done away from the MTS Arena. The Main Operation Control Room in Figure 4.11 provide consoles where planning and off-line session with 3DROCS can be conduced.

4.2 HW: the robotic platform ExoTeR and the Landing Platform mock-up

The ExoMars Testing Rover (ExoTeR) is an ExoMars half scaled dimension prototype, which includes mock-ups of the Solar array, WISDOM antennas, and Drill Box. Its locomotion configuration is very similar to the ExoMars Rover one: 6 driving, 4 steering and 6 deployment actuators. The Rover also includes Mast and Pan&Tilt subsystem, and has 3 imagers mounted: the PanCam, the NavCam and the LocCam.
ExoTeR generates the following telemetry:

Figure 4.11: ROCC Main Operations Control Room (Credit: ALTEC).

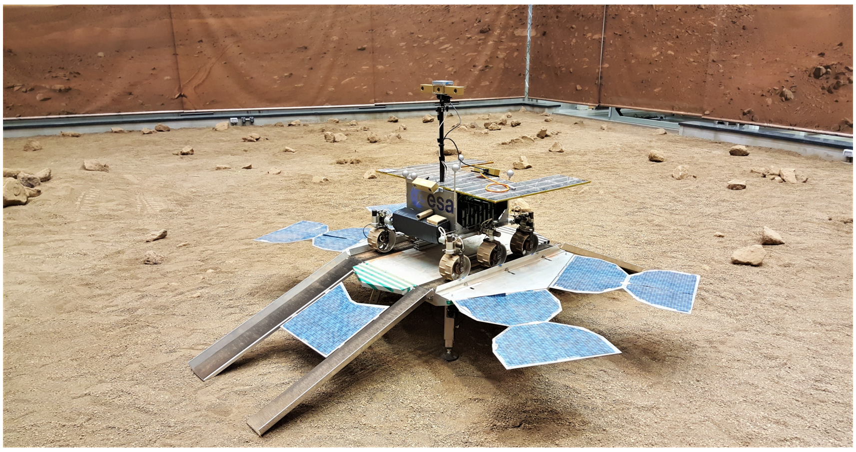


Figure 4.12: ExoTeR on the Landing Platform mock-up (Credit: ALTEC).

- date and time;
- gnc state (x, y, z, roll, pitch and yaw);
- locomotion state (wheel speed and orientation);
- mast state (PTU values);
- images.

ExoTeR is controlled via APs, using TCs equivalent to ExoMars Rover Tasks and Actions. Activities actually run are Locomotion Deployment, Driving (follow path) and Imaging (NavCam, LocCam, PanCam WAC), while all other activities, such as the Solar Arrays deployment, the Mast deployment and the umbilical attachment, are simulated. When the Mast is considered stowed there are consequences on the image acquisition, DEM creation and projections in the 3D scenes. In this case the NavCam is mounted on the rear of ExoTeR, to simulate the Mast not deployed.

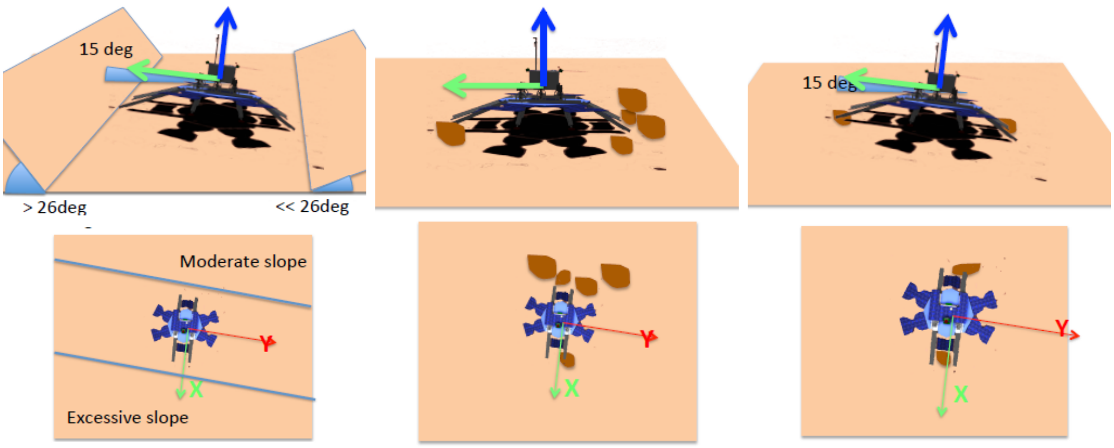
The Landing Platform mock-up is a mechanical system allowing the Rover to deploy and Egress. The Landing Platform incorporates ramps and 4 cameras placed on the corners. The mounted solar arrays mock-up simulate the volumes and view angles, and adjustable feet allow for attitude of the platform to be set to mimic a rough terrain.

The Landing Platform is commanded via APs in RAPDL. The only activity actually simulated on the landing platform is to take pictures.

The declared and to be tested limitations of the Rover are those for a secure Egress, the most critical operation of the entire surface mission, and for safe locomotion.
When ExoTeR is on the LP there are nominal conditions if the Lander has a slope less than 15°, if the ramps do not exceed 20° inclination, and if the step at the end of the ramp (when rocks are underneath it), is not greater than 10 *cm*. A path is considered to be safe for ExoTeR when there are no obstacles higher than 12.5 *cm* and the inclination of the ground does not exceed 26°.

With the use of ExoTeR and the LP mock-up MTS operators can create different Egress scenarios that must be tested. For each scenario the operator in the ROCC Operation Room must receive TM, and overcome contingencies that ExoTeR will face when it descends from the Lander, during its locomotion.

Figure 4.13 shows different scenarios which can be recreated in MTS with ExoTeR and the LP mock-up.



(a) Scenario 1. (b) Scenario 2. (c) Scenario 3.

Figure 4.13: Scenarios which can be recreated in MTS. ExoTeR x_{body}, y_{body} and z_{body} in green, red and blue, respectively (Credit: ALTEC).

Scenario 1 (Figure 4.13(a)) allows a feasible rear Egress. The Lander is tilted upwards, but slopes of ramps are within threshold. Ahead of the Rover there is an excessive slope. Scenario 2 (Figure 4.13(b)) allows a feasible front Egress. The Lander is flat, and inclination

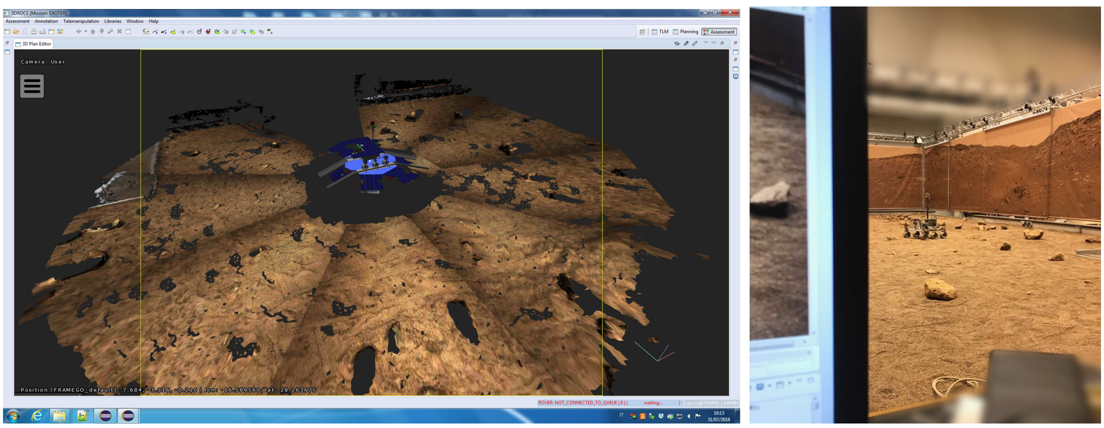
of all ramps are within threshold. The ramp front-left sits on a rock, creating a step lower than threshold. There is a non-negotiable boulder field ahead of rear ramps.
Scenario 3 (Figure 4.13(c)) allows a feasible rear Egress. The Lander is tilted upwards, but slopes of ramps are within threshold. The ramp rear-left sits on a rock, creating a step lower than threshold. There is a big rock in the middle of front ramps, too high to be overcome.

Egress difficulties which could be faced on Mars, and to be detected during a test are:

- excessive slope of the terrain;
- obstacles at the end of the ramps;
- ramp with final step, maybe because of not visible rocks (*trampoline* case);
- ramp with excessive slope;
- high obstacles in the middle of the ramps;
- the LP landing has generated excessive slopes all around (*self-crater* case).

4.3 SW: the Rover mission planning and execution tool 3DROCS

The main tool used during tests is the 3DROCS in on-line and off-line sessions. It allows the user to manage and run any APs in RAPD language.



(a) 3DROCS tool in off-line session, 3D Cell in the Assessment window.

(b) ExoTeR commanded by 3DROCS in on-line session (Credit: ALTEC).

Figure 4.14: 3DROCS on-line session.

A 3DROCS on-line session "per SOL" or "per AP" should be used: creation and closure of an on-line sessions re-creates real communication slots. The beginning of the session simulates the reception of TCs. Afterwards, the Rover begins to execute the AP and every telemetry, including images, are recorded in the specific directory of this on-line session. At the end of the session this folder can be compressed and used as TM file to forward to the Ground, hence mimicking a communication session.

3DROCS in off-line session imports, displays and provides the operator with the TM, the images and the DEMs generated by the Rover. Using this software reduces time spent for the AP creation and increases the perception of ExoTeR status.
Go/NoGo criteria and action to be considered in the decision process that is carried out in an off-line session are the following:

- field not clear from rocks;
- Rover on a rim of a crater;
- LP landed between two slopes;
- availability of a further path after the Egress;
- possible step at the end of the ramp;
- slippage induced by a very steep slope;
- risk of getting stuck;
- images polluted by sun glare;
- addition images required to make decision;
- use of incomplete wheel deployment, before the full one, to increase stability;
- wheel-walking to reduce slippage or to overcome steps.

Chapter 5

Test campaigns

5.1 Dry run

ExoTer arrived at Altec in June 2018. ESTEC employees followed the Rover commissioning to introduce it to the MTS team, see Figure 5.1.

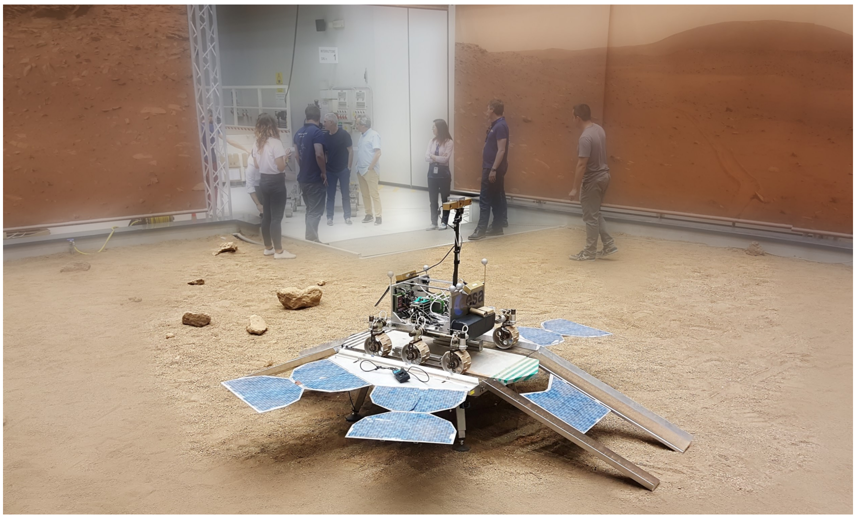


Figure 5.1: ExoTeR commissioning, executed under ESTEC supervision (Credit: Altec).

In the early days of ExoTeR in Altec, we tested most of its abilities. Since PLTE operations test campaign have already been conducted in ESTEC, the re-execution of the PLTE APs was used as a dry run.

PLTE operations cover six SOLs. Each SOL was simulated with an on-line session. During this practice run the off-line session and the TM data assessment were conducted in the MTS, with the same console used in the on-line session and with the possibility to directly observe ExoTeR in the Arena. This solution reduced the chance of a Egress failure, as the test aimed at our familiarization with ExoTeR and 3DROCS.

For each on-line session, therefore each SOL, the following information is presented:

- the objectives of the session;
- the executed Activity Plan;
- the generated products;
- the final state of the system;
- the assessment of the HK data;
- the assessment of the environment data (Images, DEMs).

5.1.1 PLTE #0

Description

Prepare the Rover in stowed configuration and reset the pose on top of the Surface Platform.

Activity Plan

The Rover executes the Activity Plan 5.1, loaded during the on-line session.

```
EXEC    A1,     Deployment_All (1,-95.0,100);
EXEC    A2,     GNC_Update (1,0.0,0.0,0.44,0.0,0.0,0.0);
EXEC    A3,     MAST_PTU_MoveTo (0, 0.0, 0.0, 15.0);

END_SOL;
```

Activity Plan 5.1: PLTE #0.

Generated output

No products are generated.

Initial and final states of the system

The initial state of the system in this session is meaningless because the configuration is yet to be initialized.

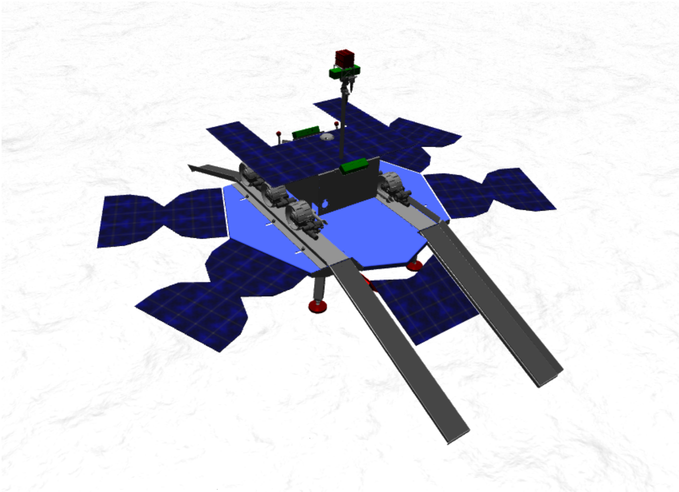


Figure 5.2: 3D scenario on 3DROCS - PLTE#0, after a successful landing.

The final state consists of ExoTeR positioned on the platform, with the locomotion subsystem and the Mast stowed. In Figure 5.2 the 3D scenario is shown: ExoTer on the LP, with the locomotion subsystem withdrawn. The Mast deployment is simulated, and evn if it is supposed to be stowed, it looks deployed in the 3D scenario.

Assessment of the session

After the closure of the on-line session executed in the Planning window, it is possible to assess its telemetry and products in an off-line session.

In a SOL like this one there are no TCs requiring the generation of TM proving the advancement of the commanded process. However, TM data are recorded. They specify the state of the locomotion subsystem, constantly monitored.

The only relevant TM data is:
`1530717814518 GNC_STATE 1 1530717814518 4.0 0.0 0.0 0.44 -1.4 2.3 0.0 4 0`
GNC state is expressed in this way:
`time GNC_STATE 1 time 4.0 x y z roll pitch yaw 4 0`

No environment data to be assessed have been produced.
The test starts from the next session, with the landing and the LP appendices deployment executed successfully.

5.1.2 PLTE #1

Description

First entire SOL on Mars.

Main activities:

- Rover Module check-out.
- LocCam and NavCam image and DEM acquisition.

Activity Plan

The Rover executes the Activity Plan 5.2.

Lines beginning with # are comments explaining the controlled actions. Commented lines are skipped by the AP file reader.

```
# Waits the transition Night to Day
EXEC    A1,     RV_WakeUp;
EXEC    A2,     MMS_WaitAbsTime(33390); # Wait (09:00)
EXEC    A3,     GNC_MonitoringOnly; # IMU Switch On for Check-out
EXEC    A4,     MMS_WaitAbsTime(50085); # Wait (13:30 - suitable time to opimize energy balance, minimize warmup times, battery SoC at the end of the SOL)
EXEC    A5,     ADEs_Activate(3,3,10800,-50,10800); # RV ADE S/S Switch On for Check-out
EXEC    A6,     MMS_WaitRelTime(300); # Wait 5min
EXEC    A7,     ADEs_DeActivate(3000);
EXEC    A8,     PanCam_Initialise(1,1,1); # PanCam is checked out as NavCam redundancy
EXEC    A9,     MMS_WaitRelTime(300);
EXEC    A10,    PanCam_PIUSwitchOff(1,1);

# LocCam and NavCam Stereo-image and DEM acquisition (with Rover Stowed and Mast folded)
EXEC    A11,    NAVCAM_ACQ(0,5,0);
EXEC    A12,    LOCCAM_ACQ(0,5,0);
EXEC    A13,    MMS_WaitAbsTime(63070); # Wait (17:00) and switch off IMU
EXEC    A14,    GNC_SwitchOff;

#Wait the transition Day to Night
EXEC    A15,    RV_Prepare4Night;
EXEC    A16,    MMS_WaitAbsTime(89040); # Wait until midnight

END_SOL;
```

Activity Plan 5.2: PLTE #1.

Camera acquisitions are the only command actually executed. Other activities are simulated by waiting a period of time, corresponding to their execution.

Generated output

The Rover generates the products presented in Figure 5.3.

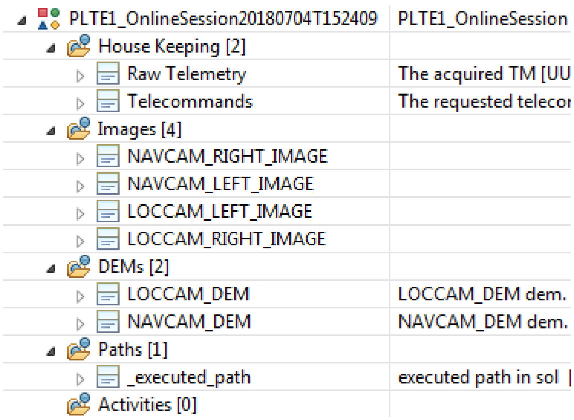


Figure 5.3: Product imported from the PLTE#1 on-line session.

In the directory of this on-line session there are a TC a the TM text files.

In the on-line session 4 images have been acquired: NavCam left and right, LocCam left and right. These images allowed the return of 2 DEMs. With the Mast stowed the NavCam created a DEM of the rear part of the set-up, the LocCam created a DEM of the front, capturing all the LP ramps.

Final state of the system

In the 3D scenario (see Figure 5.4) it is possible to see ExoTer on the LP, with the locomotion subsystem stowed, and with the DEMs produced.

Assessment of the session

During this session it is possible to assess the slope of the ramps. Specifically, if an image acquired from NavCam or LocCam is loaded into the Assessment window, the slope can be retrieved.

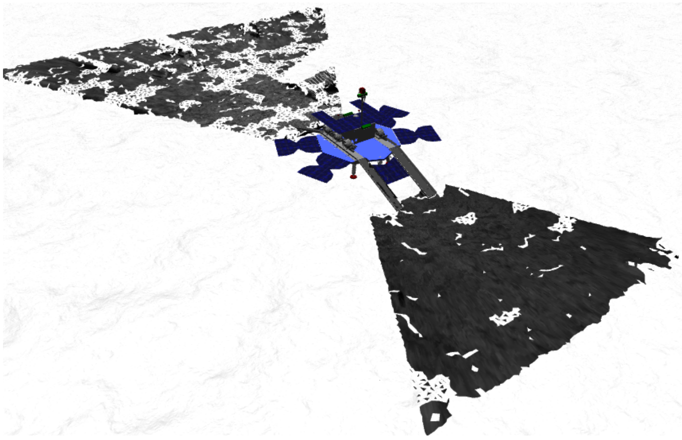
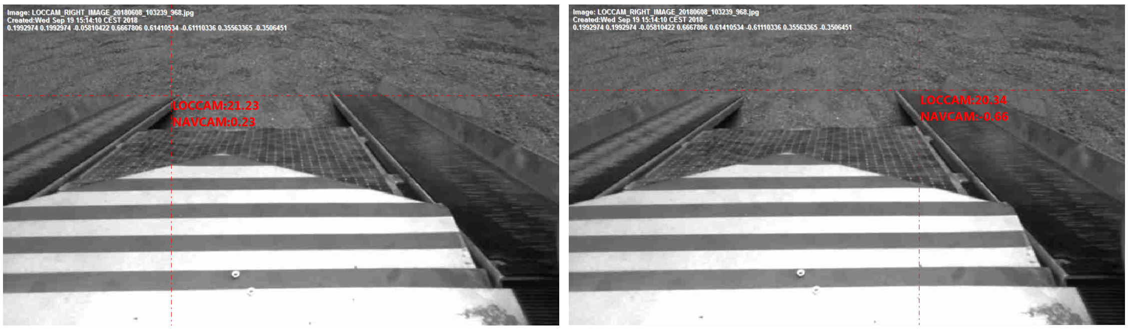


Figure 5.4: 3D scenario on 3DROCS - DEMs generated in the PLTE#1 SOL has been projected.



(a) Front left ramp.

(b) Front right ramp.

Figure 5.5: Slope of the ramps.

The 3DROCS allows us to interact with the acquired image, obtaining information such as the slope (see Figure 5.5). The data corresponding to the camera of interest can be read. For example LocCam images are shown here: the front left ramp slope is 21.23° and the front right ramp slope is 20.34°.

5.1.3 PLTE #2

Description

Second SOL on Mars.

Main activities:

- Release of Mast hold-down.

- Mast deployment.
- LocCam and NavCam panorama image acquisition.

Activity Plan

The Rover executes the Activity Plan 5.3.

```
# Waits the transition Night to Day
EXEC    A1,     RV_WakeUp;
EXEC    A2,     MMS_WaitAbsTime(33390); # Wait (09:00)
EXEC    A3,     GNC_MonitoringOnly; # IMU Switch On for Check-out
EXEC    A4,     MMS_WaitAbsTime(46375); # Wait (12:30)
EXEC    A5,     ADEs_Activate(3,3,10800,-50,10800);
EXEC    A6,     GNC_SwitchOff;

EXEC    A7,     Deploy_Mast; # Mast Deployment

EXEC    A8,     GNC_MonitoringOnly;
EXEC    A9,     MAST_PAN_Initialise(7200,0);
EXEC    A10,    MAST_TILT_Initialise(7200,0);

# WAIT_ACTIVITY_END     A7; # In this case A7 is only simulated

# NavCam panorama images acquisition
EXEC    A11,    MAST_PTU_MoveTo(1,-230,45,30);
EXEC    A12,    NAVCAM_ACQ(0,3,0);
EXEC    A13,    MAST_PTU_MoveTo(1,-180,45,20);
EXEC    A14,    NAVCAM_ACQ(0,3,0);
EXEC    A15,    MAST_PTU_MoveTo(1,-120,45,20);
EXEC    A16,    NAVCAM_ACQ(0,3,0);
EXEC    A17,    MAST_PTU_MoveTo(1,-60,45,20);
EXEC    A18,    NAVCAM_ACQ(0,3,0);
EXEC    A19,    MAST_PTU_MoveTo(1,0,45,20);
EXEC    A20,    NAVCAM_ACQ(0,3,0);
EXEC    A21,    MAST_PTU_MoveTo(1,50,45,20);
EXEC    A22,    NAVCAM_ACQ(0,3,0);
EXEC    A23,    MAST_PAN_SwitchOff;
EXEC    A24,    MAST_TILT_SwitchOff;
EXEC    A25,    ADEs_DeActivate(3000);

# LocCam images acquisition
EXEC    A26,    LOCCAM_ACQ(0,3,0);

EXEC    A27,    MMS_WaitAbsTime(63070); # Wait (17:00) and switch off IMU
EXEC    A28,    GNC_SwitchOff;

#Wait the transition Day to Night
```

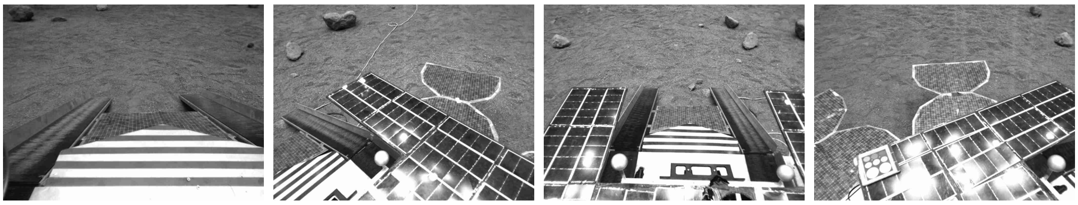
```
41 EXEC    A23,    RV_Prepare4Night;
42 EXEC    A30,    MMS_WaitAbsTime(89040); # Wait until midnight
43
44 END_SOL;
```

Activity Plan 5.3: PLTE #2.

Camera acquisitions are the only command actually executed. Other activities are simulated.

Generated output

In the directory of the last on-line session there are a TC and a TM text file and 7 images (see Figure 5.6).



(a) LocCam acquisition. (b) NavCam 1st acquisition. (c) NavCam 2nd acquisition. (d) NavCam 3rd acquisition.

(e) NavCam 4th acquisition. (f) NavCam 5th acquisition. (g) NavCam 6th acquisition.

Figure 5.6: PLTE#2 products.

LocCam and NavCam acquisitions allowed calculation of 7 DEMs all around ExoTeR. The Mast has been simulatively deployed during the AP, and so the NavCam has been manually moved on the top. `EXEC A7, Deploy_Mast` is the command used, at line 9 of the AP 5.3. The DEM projection in the 3D scenario takes into account this Mast status, so it is important that the deployment of the Mast is commanded during an AP.

Final state of the system

In the 3D scenario (see Figure 5.7) it is possible to see ExoTer on the LP, with the locomotion subsystem stowed, and with the DEMs produced.

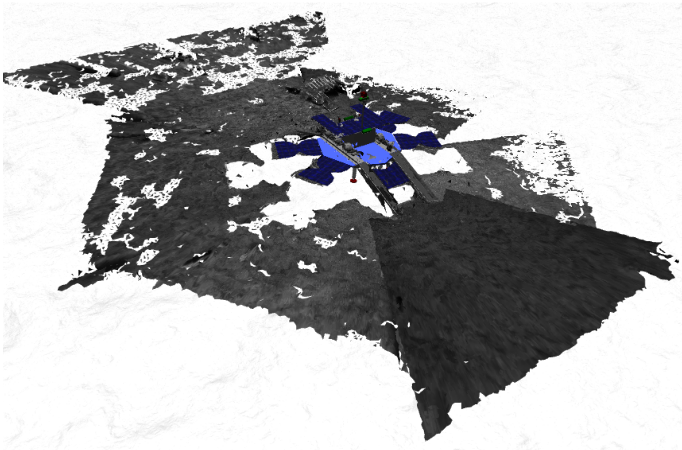


Figure 5.7: 3D scenario on 3DROCS - DEMs generated in the PLTE#2 SOL has been projected.

Assessment of the session

Figure 5.8 is a 3DROCS tool product, returned by the assessment of TM data relating the PTU.

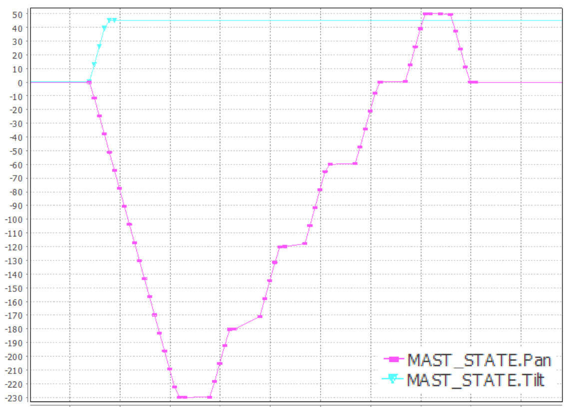


Figure 5.8: PLTE#2 SOL significant TM values relating the PTU.

At line 16 of the AP 5.3, it is possible to see that the PTU has to orientate the Nav-Cam to $-230°$ value of Pan and $45°$ value of Tilt. The command used is: `EXEC A21, MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s])`.

Then the Tilt motor is stopped. The Pan value goes to $-180°$, $-120°$, $-60°$, $0°$ and $50°$, following the commands at line 18, 20, 22, 24 and 26, respectively.

Figure 5.8 attests the executed commands.

5.1.4 PLTE #3

Description

Third SOL on Mars.

Main activities:

- Release of Rover Body Hold-Down Mechanisms.
- Locomotion subsystems deployment.
- Rover stand-up.

Activity Plan

The Rover executes the Activity Plan 5.4.

```
# Waits the transition Night to Day
EXEC    A1,     RV_WakeUp;
EXEC    A2,     MMS_WaitAbsTime(33390); # Wait (09:00)
EXEC    A3,     GNC_MonitoringOnly; # IMU Switch On for Check-out
EXEC    A4,     MMS_WaitAbsTime(46375); # Wait (12:30)
EXEC    A5,     ADEs_Activate(3,3,10800,-50,10800);
EXEC    A6,     GNC_SwitchOff;
EXEC    A7,     Release_Body; # Release of Rover Body Hold-Down Mechanisms

# Rover Stand-Up
EXEC    A8,     Deployment_All(1,0,90); # Locomotion subsystems deployment

# Update of the Rover own knowledge of raised position
EXEC    A9,     GNC_Update(1,0.0,0.0,0.57,0.0,0.0,0.0);
EXEC    A10,    ADEs_DeActivate(3000);
EXEC    A11,    MMS_WaitAbsTime(63070); # Wait (17:00) and switch off IMU
EXEC    A12,    GNC_SwitchOff;

#Wait the transition Day to Night
EXEC    A13,    RV_Prepare4Night;
EXEC    A14,    MMS_WaitAbsTime(89040); # Wait until midnight

END_SOL;
```

Activity Plan 5.4: PLTE #3.

Locomotion subsystem deployment is the only command actually executed. Other activities are simulated.

Generated output

No images are generated. In the session directory there are only a TM and a TC text file.

Final state of the system

The release of the hold mechanism, securing the Rover to the LP, is simulated. At the end of PLTE #3 SOL, ExoTeR is on the LP with the locomotion subsystem successfully deployed (see Figure 5.9).

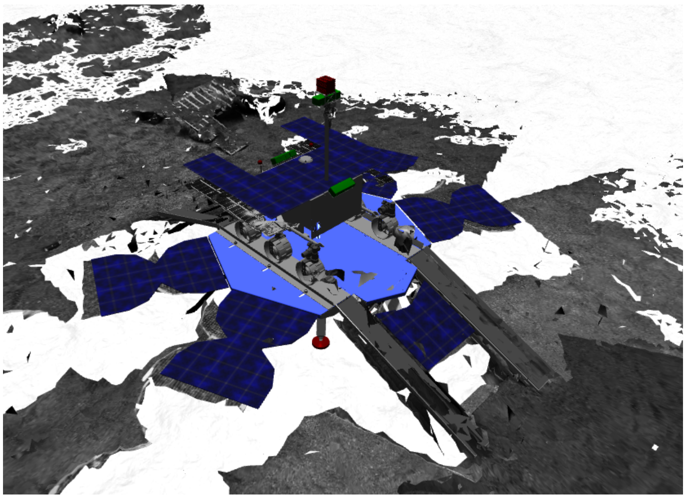


Figure 5.9: 3D scenario on 3DROCS - ExoTeR at PLTE #3 SOL on the LP, with the locomotion subsystem deployed.

Assessment of the session

Figure 5.10 is a 3DROCS tool output, returned by the assessment of TM data relating the locomotion subsystem.

At line 11 of the AP 5.4, the command `EXEC A8, Deployment_All(1,0,90)` is used to deploy the locomotion subsystem. Figure 5.10 attests the executed command. Figure 5.9 shows the locomotion subsystem deployed.

With the close-up, see Figure 5.11, it is possible to see that the DEMs generated has some holes in the area covered by the LP solar array. One of the goals of tests executed in MTS is to understand the view angles, with the Rover on the LP.

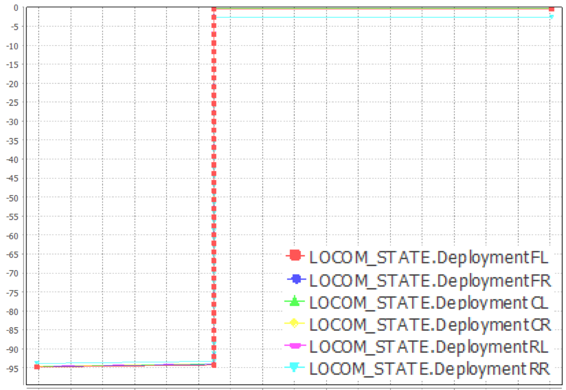
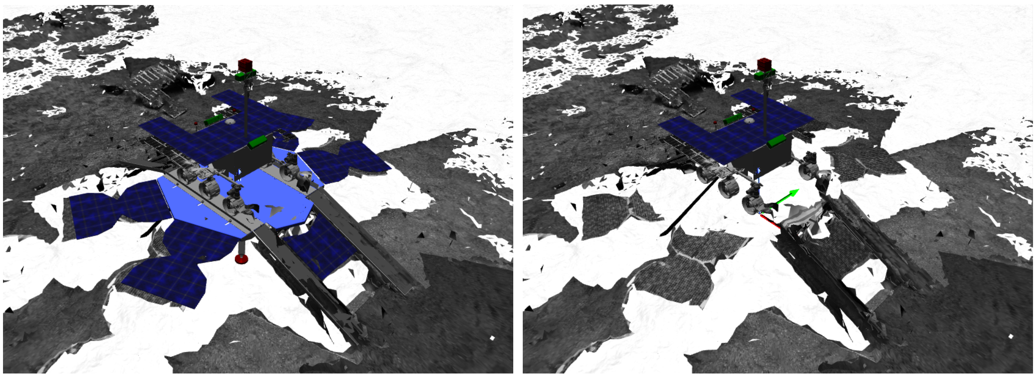


Figure 5.10: PLTE#3 SOL significant TM values relating the locomotion subsystem.



(a) With the LP depicted. (b) Without the LP depicted.

Figure 5.11: PLTE#3 - All the DEMs that have been generated up to this point.

5.1.5 PLTE #4

Description

Fourth SOL on Mars.

Main activities:

- Rover Solar Array deployment
- Rover UHF communication commissioning

Activity Plan

The Rover executes the Activity Plan 5.5.

```
# Waits the transition Night to Day
EXEC    A1,     RV_WakeUp;
EXEC    A2,     MMS_WaitAbsTime(33390); # Wait (09:00)
EXEC    A3,     GNC_MonitoringOnly; # IMU Switch On for Check-out
EXEC    A4,     MMS_WaitAbsTime(46375); # Wait (12:30)
EXEC    A5,     ADEs_Activate(3,3,10800,-50,10800);
EXEC    A6,     GNC_SwitchOff;

# Rover Solar Array Deployment
EXEC    A7,     Deploy_LEFT_SA;
EXEC    A8,     Deploy_RIGHT_SA;

EXEC    A9,     ADEs_DeActivate(3000);
EXEC    A10,    MMS_WaitAbsTime(63070); # Wait (17:00) and switch off IMU
EXEC    A11,    GNC_SwitchOff;

#Wait the transition Day to Night
EXEC    A12,    RV_Prepare4Night;
EXEC    A13,    MMS_WaitAbsTime(74200); # Wait until planned communication window (20:00)
EXEC    A14,    RV_Prepare4Comms; # Prepare RV for communication
EXEC    A15,    MMS_WaitAbsTime(76055); # Wait until communication is performed (20:30)
EXEC    A16,    RV_PostComms; # Unconfigure the RV after communication
EXEC    A17,    MMS_WaitAbsTime(89040); # Wait until midnight

END_SOL;
```

Activity Plan 5.5: PLTE #4.

Activities are all simulated.

Generated output

No products are generated.

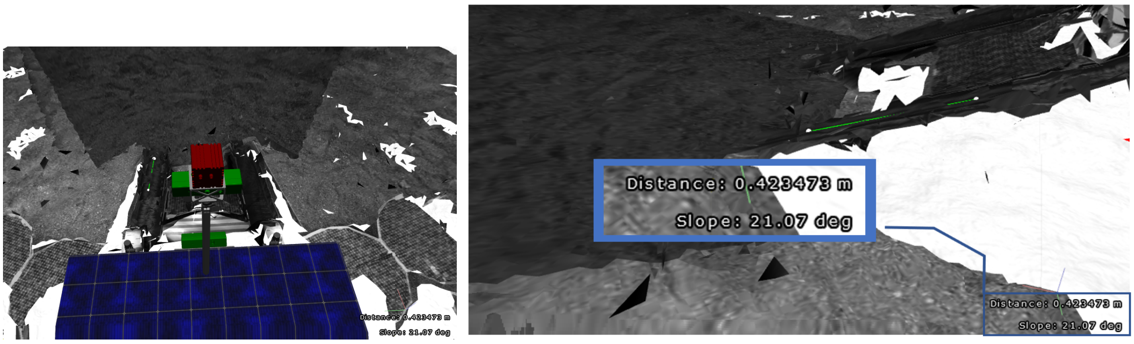
Final state of the system

During the PLTE #4 SOL only simulated activities have been commanded. The Rover solar array has been deployed and the Rover communication subsystem has been commissioned. All of this happens in a simulated way, waiting some time.

Therefore, the final state of the system is the same of the PLTE #3 SOL shown in Figure 5.9.

Assessment of the session

In an assessment of the products generated up to this session, a preliminary evaluation of the Egress direction is executed.



(a) View of the possible Egress direction. (b) Measurement of distance and slope on DEM generated.

Figure 5.12: 3D scenario in the assessment window.

Figure 5.12 shows action permitted by 3DROCS.
A front Egress seems possible (see Figure 5.12(a)), and the LocCam DEM allows the user to measure the ramp slope. Using the *ruler-tool*, distance and slope between two DEM points is shown in the bottom-right part of the 3D scenario (see Figure 5.12(b)). This measurement read a 21.07° ramp slope in the front of the LP, very similar to data showed in Figure 5.5.

In the following SOL an overview of farther place can be commanded, to ensure escape possibilities after a successful Egress.

5.1.6 PLTE #5

Description

Fifth SOL on Mars.

Main activities:

- Umbilical separation.
- LocCam and PanCam panorama image acquisition.

Activity Plan

The Rover executes the Activity Plan 5.6.

```
# Waits the transition Night to Day
EXEC    A1,     RV_WakeUp;
EXEC    A2,     MMS_WaitAbsTime(33390); # Wait (09:00)
EXEC    A3,     GNC_MonitoringOnly; # IMU Switch On for Chekout
EXEC    A4,     MMS_WaitAbsTime(46375); # Wait (12:30)
EXEC    A5,     ADEs_Activate(3,3,10800,-50,10800);
EXEC    A6,     GNC_SwitchOff;

EXEC    A7,     Release_Umbilical; # Umbilical Separation only
   simulated

EXEC    A8,     GNC_MonitoringOnly;
EXEC   A9,      MAST_PAN_Initialise(7200,0);
EXEC    A10,    MAST_TILT_Initialise(7200,0);
# WAIT_ACTIVITY_END     A9; # In this case A9 is only simulated

# PanCam panorama images acquisition
EXEC    A11,    MAST_PTU_MoveTo(1,-230,25,30);
EXEC    A12,    PANCAM_ACQ(0,3,0);
EXEC    A13,    MAST_PTU_MoveTo(1,-190,25,20);
EXEC    A14,    PANCAM_ACQ(0,3,0);
EXEC    A15,    MAST_PTU_MoveTo(1,-150,25,20);
EXEC    A16,    PANCAM_ACQ(0,3,0);
EXEC    A17,    MAST_PTU_MoveTo(1,-110,25,20);
EXEC    A18,    PANCAM_ACQ(0,3,0);
EXEC    A19,    MAST_PTU_MoveTo(1,-70,25,20);
EXEC    A20,    PANCAM_ACQ(0,3,0);
EXEC    A21,    MAST_PTU_MoveTo(1,-30,25,20);
EXEC    A22,    PANCAM_ACQ(0,3,0);
EXEC    A23,    MAST_PTU_MoveTo(1,10,25,20);
EXEC    A24,    PANCAM_ACQ(0,3,0);
EXEC    A25,    MAST_PTU_MoveTo(1,50,25,20);
EXEC    A26,    PANCAM_ACQ(0,3,0);
EXEC    A27,    MAST_PTU_MoveTo(1,0,45,20);
EXEC    A28,    PANCAM_ACQ(0,3,0);

EXEC    A29,    MAST_PAN_SwitchOff;
EXEC    A30,    MAST_TILT_SwitchOff;
EXEC    A31,    ADEs_DeActivate(3000);

# LocCam images acquisition
EXEC    A32,    LOCCAM_ACQ(0,3,0);

EXEC    A33,    MMS_WaitAbsTime(63070); # Wait (17:00)
EXEC    A34,    GNC_SwitchOff;

#Wait the transition Day to Night
EXEC    A35,    RV_Prepare4Night;
```

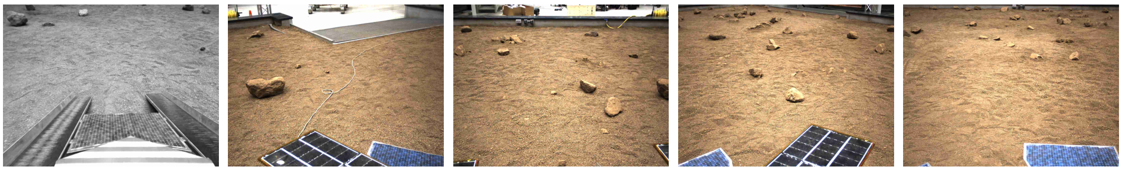
```
EXEC    A36,    MMS_WaitAbsTime(74200); # Wait until planned communication window (20:00)
EXEC    A37,    RV_Prepare4Comms; # Prepare RV for communication
EXEC    A38,    MMS_WaitAbsTime(76055); # Wait until communication is performed (20:30)
EXEC    A39,    RV_PostComms; # Unconfigure the RV after communication
EXEC    A40,    MMS_WaitAbsTime(89040); # Wait until midnight

END_SOL;
```

Activity Plan 5.6: PLTE #5.

Camera acquisitions are the only command actually executed. Other activities are all simulated.

Generated output

In the PLTE #5 SOL on-line session 10 images are acquired, (see Figure 5.13), and a TM a TC text files are created.



(a) LocCam acquisition. (b) PanCam 1st acquisition. (c) PanCam 2nd acquisition. (d) PanCam 3rd acquisition. (e) PanCam 4th acquisition.

(f) PanCam 5th acquisition. (g) PanCam 6th acquisition. (h) PanCam 7th acquisition. (i) PanCam 8th acquisition. (j) PanCam 9th acquisition.

Figure 5.13: PLTE#5 products.

LocCam and PanCam acquisition permits to produce 10 DEMs all around ExoTeR.

Final state of the system

Adding the DEMs generated in the PLTE#5 SOL to the 3D scenario, a complete perception of the environment all around the LP takes shape (see Figure 5.14).

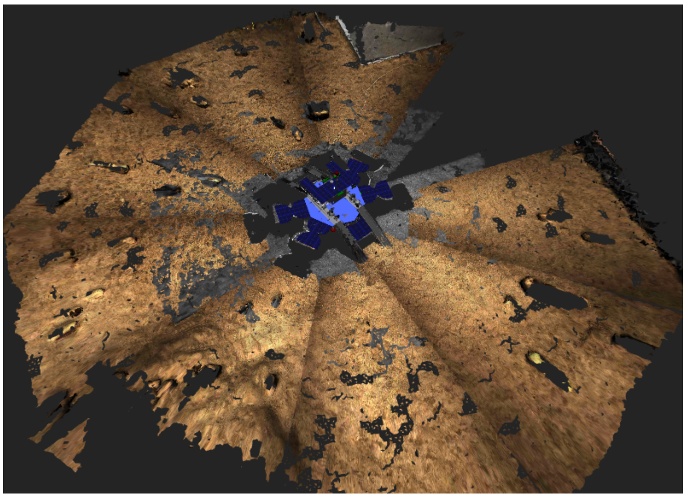
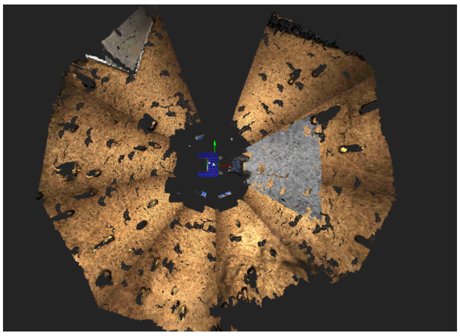


Figure 5.14: 3D scenario on 3DROCS - DEMs generated in the PLTE#5 SOL has been projected.

The PanCam has a lower Tilt than NavCam in the previous acquisitions. Therefore, the 3D reconstruction reaches farther points, permitting identification of future paths or obstacles far from the ramps.

Assessment of the session



(a) Aerial view. In the rear of the LP a boulder field.

(b) Measurement of a rock dimension.

Figure 5.15: DEMs imported from the PLTE#5 on-line session.

From an aerial view (see Figure 5.15(a)) it is possible to see a large number of rocks in front of the rear ramps. Moreover, thanks to the *ruler-tool* it is possible to measure them. In Figure 5.15(b), the size of the nearest, hence encumbering, stone is measured. At the bottom right of the Figure it is possible to read the size of the: approximately 18 *cm*. This dimension is excessive for ExoTeR to handle.

Based on these evaluations we can consider a front Egress: the ramps slope is within thresholds, there seems to be no step at the end of the ramps, and in the forward direction it is possible to visualize a post-Egress path.

5.1.7 PLTE #6

Description

Sixth SOL on Mars.

Main activities:

- Rover Egress.

Activity Plan

The Rover executes the Activity Plan 5.7.

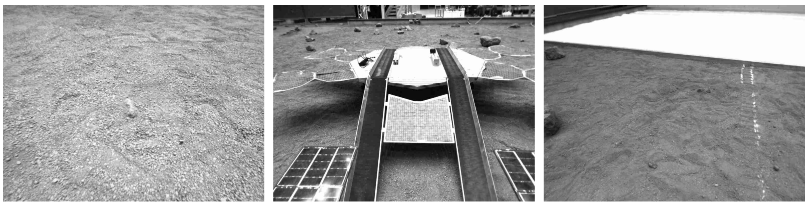
```
# Prepare RV for communication
EXEC    A1,     MMS_WaitAbsTime(14840); # Wait until planned
    communication window (4:00)
EXEC    A2,     RV_Prepare4Comms;
EXEC    A3,     MMS_WaitAbsTime(16695); # Wait until communication
    is performed(4:30)
EXEC    A4,     RV_PostComms; # Unconfigure the RV after
    communication

# Waits the transition Night to Day
EXEC    A5,     RV_WakeUp;
EXEC    A6,     MMS_WaitAbsTime(46375); # Wait (12:30)

# Rover Egress
EXEC    A7,     RV_Prepare4Travel;
EXEC    A8,     GNC_LLO(1,2.0,0.01); # Go ahead
EXEC    A8b,    GNC_Update(1,2.0,0.0,0.0,0.0,0.0,0.0); # Position
    manually undate to avoid wheel-odometry errors
EXEC    A9,     RV_SwitchOffMobility;

# move PTU to look at the back to confirm Egress and image LP
EXEC    A10,    MAST_PTU_MoveTo(1,-180,30,20);
EXEC    A11,    NAVCAM_ACQ(0,5,0);
EXEC    A12,    LOCCAM_ACQ(0,5,0);

# move PTU to look at the front again
EXEC    A13,    MAST_PTU_MoveTo(1,0,30,20);
EXEC    A14,    NAVCAM_ACQ(0,5,0);
```

```
25
26 #Wait the transition Day to Night
27 EXEC    A15,    RV_Prepare4Night;
28 EXEC    A16,    MMS_WaitAbsTime(74200); # Wait until planned
       communication window (20:00)
29 EXEC    A17,    RV_Prepare4Comms; # Prepare RV for communication
30 EXEC    A18,    MMS_WaitAbsTime(76055) ;# Wait until communication
       is performed (20:30)
31 EXEC    A19,    RV_PostComms; # Unconfigure the RV after
       communication
32 EXEC    A20,    MMS_WaitAbsTime(89040); # Wait until midnight
33
34 END_SOL;
```

Activity Plan 5.7: PLTE #6.

Travelling and image acquisitions are the only command actually executed.

Generated output



(a) LocCam acquisition. (b) NavCam 1st acquisition. (c) NavCam 2nd acquisition.

Figure 5.16: PLTE#6 products.

Figure 5.16 shows the PLTE #6 SOL pictures acquired. In this on-line session 3 images a TM and a TC text files are generated.

Figure 5.16(b) attests a successful Egress: ExoTeR is in front of the LP ramps.

At line 18 of the AP 5.7 the PTU is commanded to move to look at its back, to image the LP. At line 23 the PTU move to look at its front again, to shoot the possible future path.

Final state of the system

Having applied the final state to the 3D scenario, ExoTeR appears in front of the LP after the Egress (see Figure 5.17).

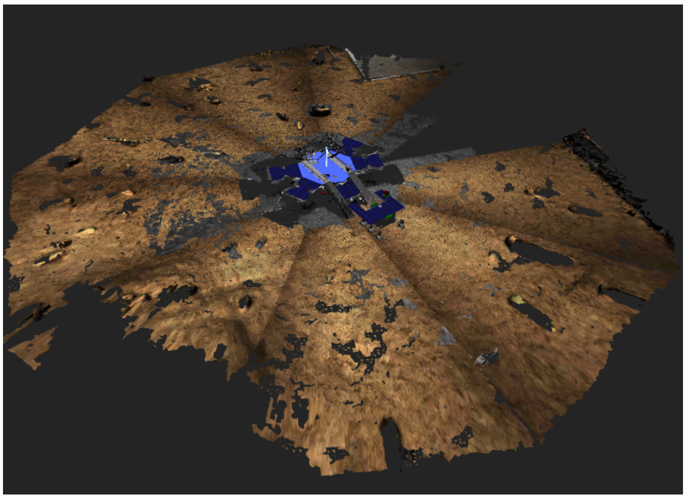
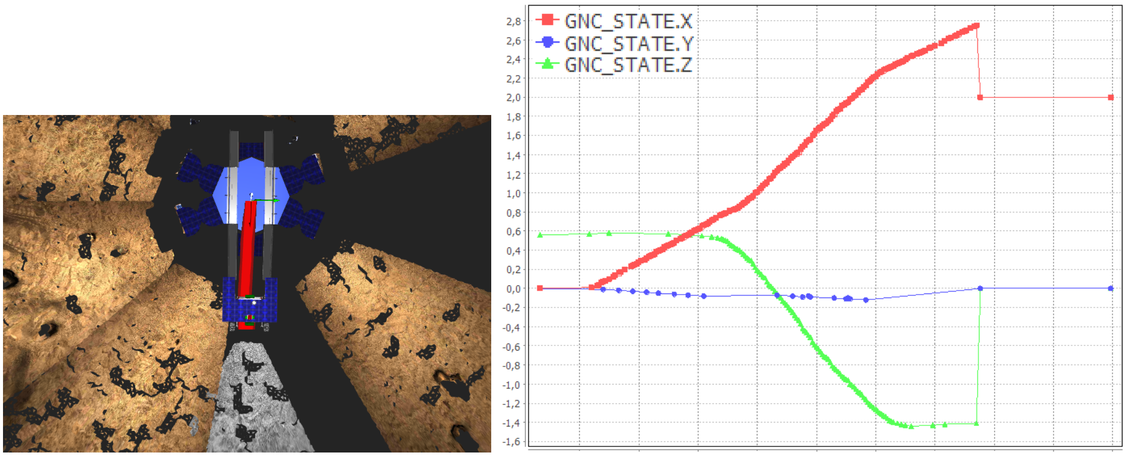


Figure 5.17: 3D scenario on 3DROCS - DEMs generated in the PLTE#6 SOL has been projected.



(a) Path executed after a successful Egress. (b) Data relating the GNC Subsystem.

Figure 5.18: PLTE#6 SOL significant TM values.

Assessment of the session

In the 3D scenario it is possible to import the path executed from the Rover, see Figure 5.18(a). The travelling action is commanded at line 13 of the AP 5.7 with `GNC_LLO(1, meters to be travelled, speed [m/s])`.

Figure 5.18(b) reports data registered during the on-line session, relating the GNC subsystem. It shows the ExoTeR position recorded during the Egress process. These data are based on the wheel-odometry. The odometry is an estimation of the position variation with respect to the known starting point coordinates. In wheel-odometry, motion sensors (encoder) mounted on the wheels are used. They register the wheel rotation, transforming it into body displacement.

Negative z values are the result of the integration of IMU and wheel-odometry data:

- The wheel-odometry attests that the wheels continue to rotate. Therefore, the body advances.
- The IMU registers the Rover nose down when it is on the ramp. Therefore, z decreases.

In reality the terrain does not allow the Rover to reach negative z, and when wheels touch the ground, at the end of the ramps, the Rover starts to straighten up. This error is corrected at line 14 of the AP 5.7, where the coordinates (x, y, z) are forced to $(2, 0, 0)$ m. This correction can also be seen in Figure 5.18(b).

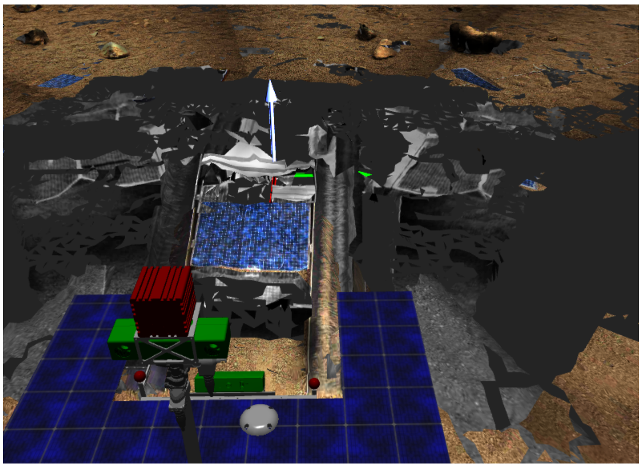


Figure 5.19: ExoTeR NavCam looking at the LP, after a successful Egress. DEM has been generated.

Figure 5.19 attests a successful Egress, and part of the LP is projected in the 3D scenario. It means that the Rover is in front of the LP, and with the camera looking at the back, the LP ramps are shot.

5.2 Johanneum Research tests

Johanneum Research (JR) is the company that generates the DEM based on stereo images collected by cameras of the ExoMars Rover. This post-processing is based on the deep knowledge of the imagers mounted on the vehicle.

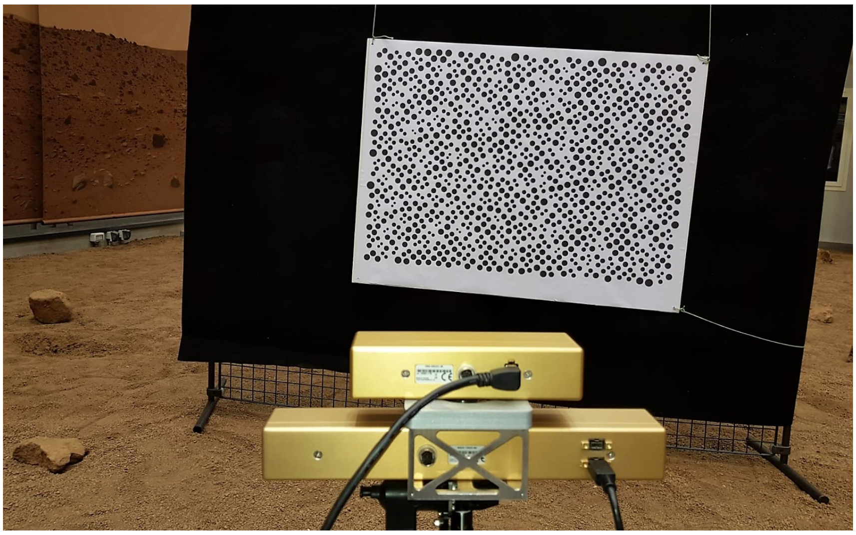


Figure 5.20: JR Test 1 set-up - NavCam (the upper camera) and PanCam (the lower) acquiring images of a calibration target with well-known point coordinates (Credit: ALTEC).

The stereo images are two different images processed using a method called stereoscopy. This method allows the perception of depth and 3-dimensional structure obtained on the basis of visual information deriving from two "eyes". All these imagers are stereo camera: a type of camera with two image sensors, simulating human binocular vision.

The geometry of a camera describes the transformations necessary to understand how a point in space is projected into the acquired image.

Camera calibration and triangulation become the main trials in the DEM generation post-processing. Calibration aims at obtaining the intrinsic and extrinsic parameters of the cameras. Triangulation is the reconstruction of the third dimension starting from information derived from 2D images. In order to apply the triangulation algorithms, the coordinates of a point localized in at least two images and the camera matrix must be known.

The camera matrix is then introduced: it merges a point in space and the corresponding point in the image taken by the camera. The point m in the image is joint to the point M in the real world, passing through the camera center of projection C.

Calibration is the process that allows the determination of the elements that make up the camera matrix, collecting all the parameters related to the nature of the camera. Once the camera matrix is known, it is possible to determine the parameters that characterize the internal structure of the camera (intrinsic parameters), and those that characterize the position and orientation of the camera with respect to an absolute reference system (extrinsic parameters). The camera matrix can also obtained analytically from the product of the matrix of intrinsic and extrinsic parameters.

The triangulation aims at obtaining information on the absolute three-dimensional coordinates of the captured object, given a pair of images obtained by two different cameras. It is important that the two cameras take photo of the same object, whose coordinates (x, y, z) have to be calculated, but from two different points of view. The calibration process contributes to obtain the characteristics of the single camera that photographs the scene. These properties are at the base of the algorithm that intersects the two projection lines coming from two cameras. There are two camera: the left camera, indicated with L, and right camera with R.

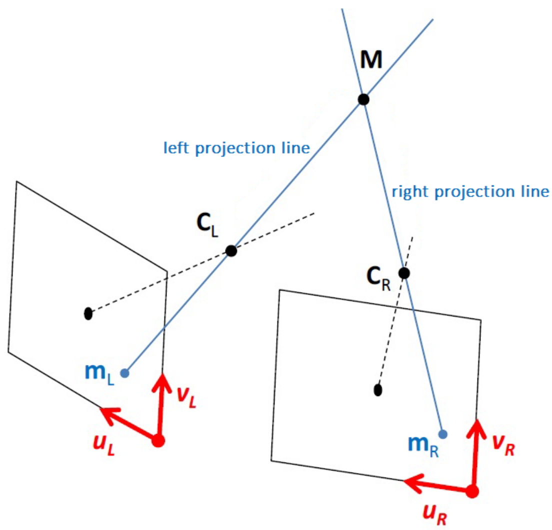


Figure 5.21: Intersection of projection lines coming from two cameras (Credit: [4] *L. Bramante "Metodi di localizzazione per robot" - MA thesis*).

Figure 5.21 shows how it is possible to obtain the 3D coordinates of the point M = (x, y, z) in space, knowing the 2D positions of points $m_L = (u_L, v_L)$ and $m_R = (u_R, v_R)$ measured on the images captured by the two cameras, and creating the two projection lines. Projection lines link M to m_L, and M to m_R, passing through C_L and C_R, respectively. C_L and C_R derive from the intrinsic and extrinsic parameters calculated during the calibration.

In order to calibrate a stereo image system assembled to a Pan&Tilt Unit jointly, several images must be taken with the sensors.

Three types of tests have been executed:

- Test 1: NavCam and PanCam calibration;

- Test 2: LocCam calibration;
- Test 3: panorama acquisitions.

A total of 1928 images have been acquired, i.e. 964 stereo pairs.

The test conducted in MTS with ExoTeR, by ROCC operators with the PanCam team, is one of the first experiences that interface the Rover and the scientific payload.

This kind of test, requiring numerous acquisitions of images from different positions, takes a long time if performed without the Rover. In fact, with a camera mounted on a tripod, the handling of it and the orientation of the camera take up a lot of time. Additional time is required to measure the attitude of the camera, information that is easily found in TM instead, thanks to the use of the PTU.

5.2.1 Test 1: NavCam and PanCam calibration

ExoTeR is steady on the ground, pointing to the target as seen in Figure 5.20.

NavCam, immediately followed by PanCam, captures 30 stereo pairs with PTU orientations in the order denoted in Table 5.1. Each capture requires the Mast orientation and the acquisition of stereo images (left and right) by the NavCam first and by the PanCam afterwards.

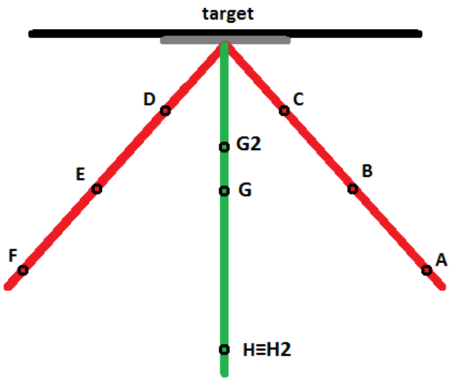
Pan → Tilt ↓	$20°$	$10°$	$0°$	$-10°$	$-20°$
$-15°$	1^{st} c.	2^{nd} c.	3^{rd} c.	4^{th} c.	5^{th} c.
$-9°$	6^{th} c.	7^{th} c.	8^{th} c.	9^{th} c.	10^{th} c.
$-3°$	11^{th} c.	12^{th} c.	13^{th} c.	14^{th} c.	15^{th} c.
$3°$	16^{th} c.	17^{th} c.	18^{th} c.	19^{th} c.	20^{th} c.
$9°$	21^{st} c.	22^{nd} c.	23^{rd} c.	24^{th} c.	25^{th} c.
$15°$	26^{th} c.	27^{th} c.	28^{th} c.	29^{th} c.	30^{th} c.

Table 5.1: JR Test 1 - Order of the captures (c.) with Pan and Tilt of the camera

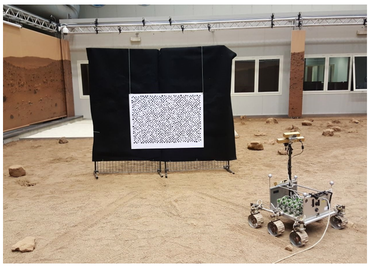
This sequence is explicitly outlined in the Activity Plan B.1 in Appendix B.
This AP uses the following commands:

```
MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s]);
NAVCAM_ACQ (0, type of the acquisition: 5=stereo, 0);
PANCAM_ACQ (0, type of the acquisition: 5=stereo, 0).
```

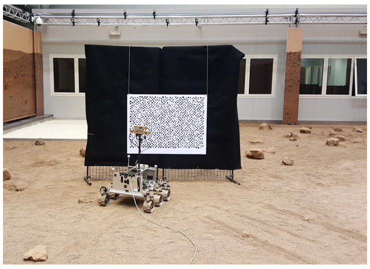
This type of sequence is repeated ten times from ten different positions of ExoTeR with respect to the target, shown in Figure 5.22 and in Table 5.2.



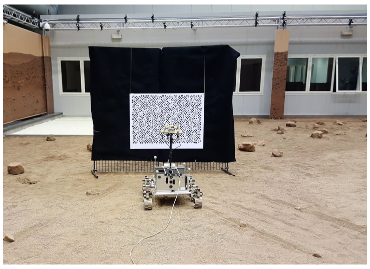
(a) ExoTer positions.



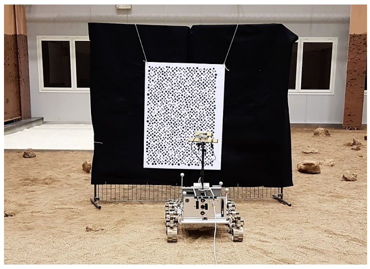
(b) Position A, similar to position B and C. Target in landscape orientation.



(c) Position D, similar to position E and F. Target in landscape orientation.



(d) Position G, similar to position H. Target in landscape orientation.



(e) Position G2, similar to position H2. Target in portrait orientation.

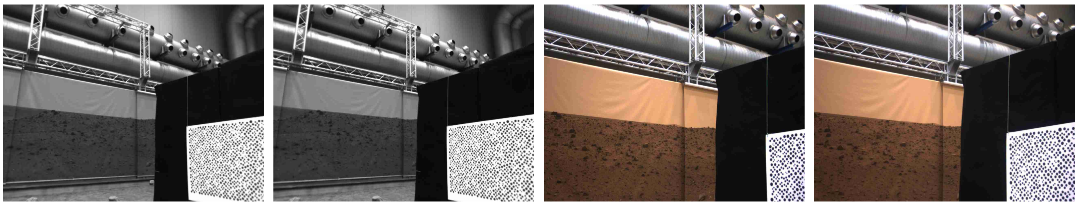
Figure 5.22: JR Test 1 - ExoTer positions (Credit: Altec).

Position	Distance Mast-target on the red line	Distance Mast-target on the green line	Orientation of the target
A	2.5 m		Landscape
B	1.75 m		Landscape
C	1 m		Landscape
D	1 m		Landscape
E	1.75 m		Landscape
F	2.5 m		Landscape
G		1.2 m	Landscape
G2		1 m	Portrait
H		2 m	Landscape
H2		2 m	Portrait

Table 5.2: JR Test 1 - Approximated ExoTer positions.

Each AP executed in a singular on-line session produces a folder. In each directory there are a TC and a TM file and 120 images (30 stereo pairs from NavCam and 30 stereo pairs from PanCam, see Figure 5.24).

Figure 5.23 shows output of a single capture of ExoTeR imagers.



(a) NavCam left image. (b) NavCam right image. (c) PanCam left image. (d) PanCam right image.

Figure 5.23: Stereo pair produced from ExoTeR in one capture, at position A.

The portion of the TM reporting the acquisition of these images is the following:

```
# Mast starts moving
# time MAST_STATE 1 time 0 0 0 0.0 Pan Tilt value value
1531316256110 MAST_STATE 1 1531316256110 0 0 0 0.0 0.0 0.0 2 35
1531316257111 MAST_STATE 1 1531316257111 0 0 0 0.0 8.17 -9.48 2 35
# Don't take care of Locomotion state TM, received periodically
1531316257111 LOCOM_STATE 1 1531316257111 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.07 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.1 0.1 0.0 0.0 3.0 1.0 0.0
# Mast keeps moving
1531316258112 MAST_STATE 1 1531316258112 0 0 0 0.0 19.7 -15.0 0 0
# Mast reaches the desired position
1531316259116 MAST_STATE 1 1531316259116 0 0 0 0.0 19.99 -14.99 0 0
# The NavCam captures the stereo images pair
1531316258327 NAVCAM_LEFT_IMAGE 1 1531316258327 mono9 780 1024 true 1 0.03724329 0.071172245 0.7529623
-0.48728213 0.39110512 -0.50309503 0.5970664
1531316258327 NAVCAM_RIGHT_IMAGE 1 1531316258327 mono9 780 1024 true 1 0.05936948 -0.048207432 0.7545038
-0.48434457 0.37513965 -0.49847248 0.6133562
1531316261117 LOCOM_STATE 1 1531316261117 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.07 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.1 0.0 0.0 0.0 2.0 1.0 0.0
# The PanCam captures the stereo images pair
1531316259770 PANCAM_LEFT_IMAGE 1 1531316259770 mono9 780 1024 true 1 0.036179695 0.12766264 0.7004876
-0.50140405 0.34110492 -0.46098408 0.64786965
1531316259770 PANCAM_RIGHT_IMAGE 1 1531316259770 mono9 780 1024 true 1 0.11832743 -0.09778807 0.7053585
-0.50140405 0.34110492 -0.46098408 0.64786965
```

Figure 5.24: Folder containing output of JR Test 1, position A on-line session.

5.2.2 Test 2: LocCam calibration

ExoTeR is steady on the Landing Platform, pointing to the target as seen in Figure 5.25.

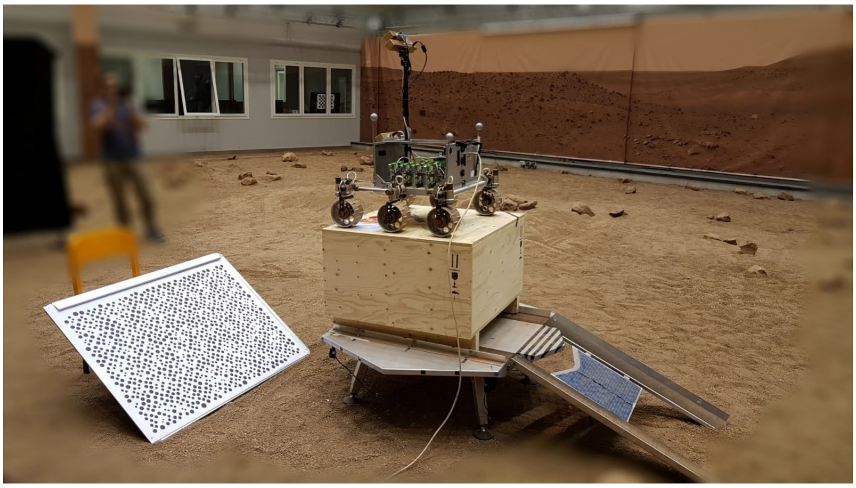


Figure 5.25: JR Test 2 set-up (Credit: ALTEC).

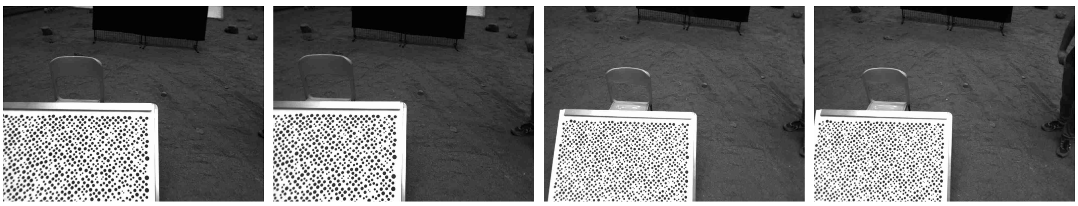
NavCam, immediately followed by PanCam, captures 100 stereo pairs.

For 100 times the target is manually moved in the field of view of the NavCam and the LocCam with different orientations and positions. NavCam keeps the same attitude for the whole session: Pan = 0° and Tilt = 40°.

The same AP (see Activity Plan B.2 in Appendix B) is launched 100 times, with these commands:

```
NAVCAM_ACQ (0, type of the acquisition: 5= stereo, 0);
LOCCAM_ACQ (0, type of the acquisition: 5= stereo, 0).
```

The on-line session folder contains 400 images (100 stereo pairs from NavCam and 100 stereo pairs from LocCam, see Figure 5.27), and a TC and a TM text files. Figure 5.26 shows output of the first AP run.



(a) LocCam left image. (b) LocCam right image. (c) NavCam left image. (d) NavCam right image.

Figure 5.26: Stereo pair produced from ExoTeR as output of the first AP run.

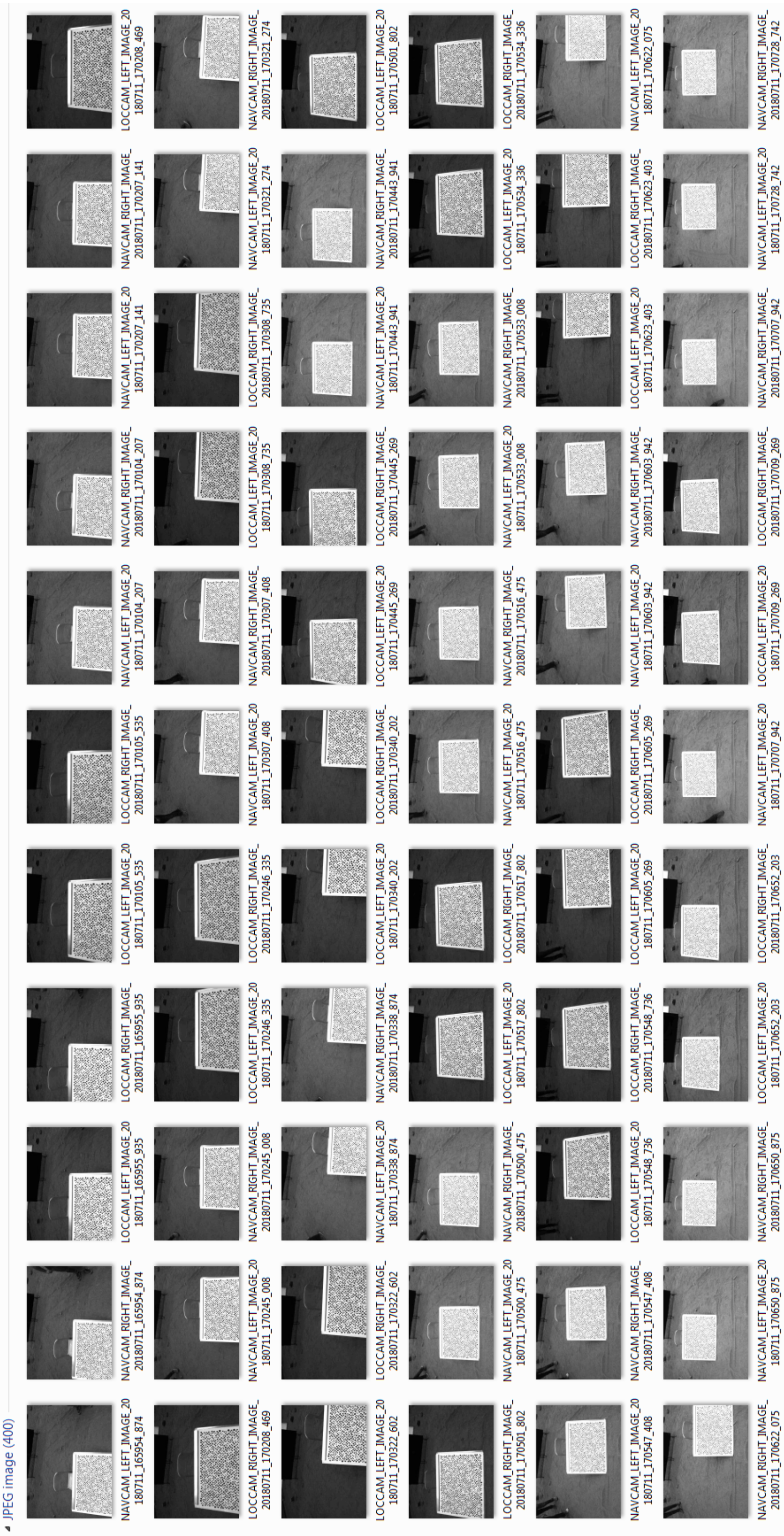


Figure 5.27: Folder containing output of JR Test 2 on-line session.

5.2.3 Test 3: panorama acquisitions

ExoTeR is placed in four different points in the MTS Arena.

From each position the LocCam captures a stereo image pair, and then the NavCam and the PanCam make a panoramic acquisition, capturing 20 stereo pairs with PTU orientations in the order denoted in Table 5.3.

Pan → Tilt ↓	$-230°$	$-200°$	$-170°$	$-140°$	$-110°$	$-80°$	$-50°$	$-20°$	$10°$	$40°$
$10°$	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}	7^{th}	8^{th}	9^{th}	10^{th}
$40°$	11^{th}	12^{th}	13^{th}	14^{th}	15^{th}	16^{th}	17^{th}	18^{th}	19^{th}	20^{th}

Table 5.3: JR Test 3 - Order of the captures with Pan and Tilt of the camera.

Each capture, during the panorama acquisition, requires the Mast orientation (Pan from $-230°$ to $40°$ with $30°$ steps, Tilt angles equal to $10°$ and $40°$) and the acquisition of stereo images (left and right) by the NavCam first and by the PanCam afterwards.

This sequence is explicitly outlined in the Activity Plan B.3 in Appendix B.
This AP uses the following commands:

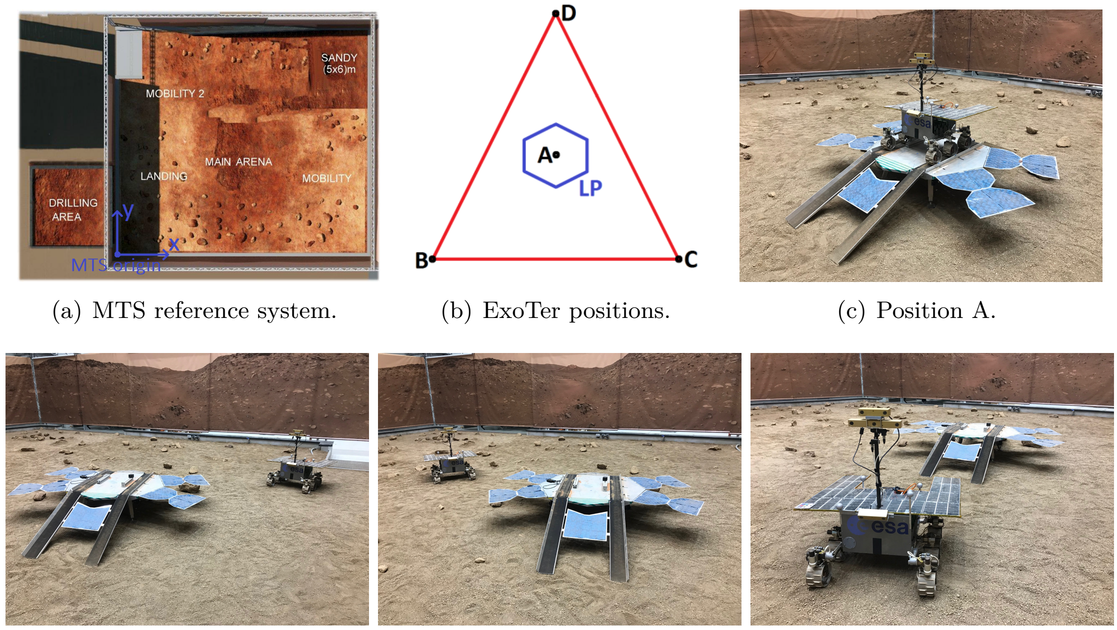
```
LOCCAM_ACQ (0, type of the acquisition: 5= stereo, 0);
MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s]);
NAVCAM_ACQ (0, type of the acquisition: 5= stereo, 0);
PANCAM_ACQ (0, type of the acquisition: 5= stereo, 0).
```

This type of sequence is repeated four times from the four different position of ExoTeR with respect to the Landing Platform mock-up (see Figure 5.28):

- **A:** On top of the LP;
- **B,C,D:** At the corners of a triangle centred into the platform, with distance:
  - AB≈ 3 m;
  - AC≈ 3 m;
  - AD≈ 3 m.

Position	X	Y
A	6.6 m	10.3 m
B	4.2 m	12.4 m
C	6.0 m	7.3 m
D	9.5 m	11.4 m

Table 5.4: JR Test 3 - Approximated ExoTer positions, obtained by OptiTrack.



(a) MTS reference system. (b) ExoTer positions. (c) Position A.

(d) Position B. (e) Position C. (f) Position D.

Figure 5.28: JR Test 3 - ExoTer positions (Credit: ALTEC).

Table 5.4 reports the four positions tracked by OptiTrack:Motive, the MTS software tracing reflective markers on a rigid body.

In this case markers are on ExoTeR (see Figure 5.29) and the position concerns the centre of mass of the main body of the Rover.

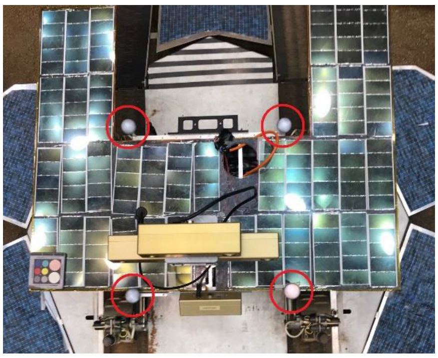


Figure 5.29: Reflective markers, allowing OptiTrack to define ExoTeR, are highlighted (Credit: ALTEC).

At each position an AP is launched, in four different on-line sessions. Each on-line session produces 82 image (a stereo pair from LocCam, 20 stereo pairs from NavCam and 20 stereo pairs from PanCam, see Figure 5.30), a TC and a TM text files.

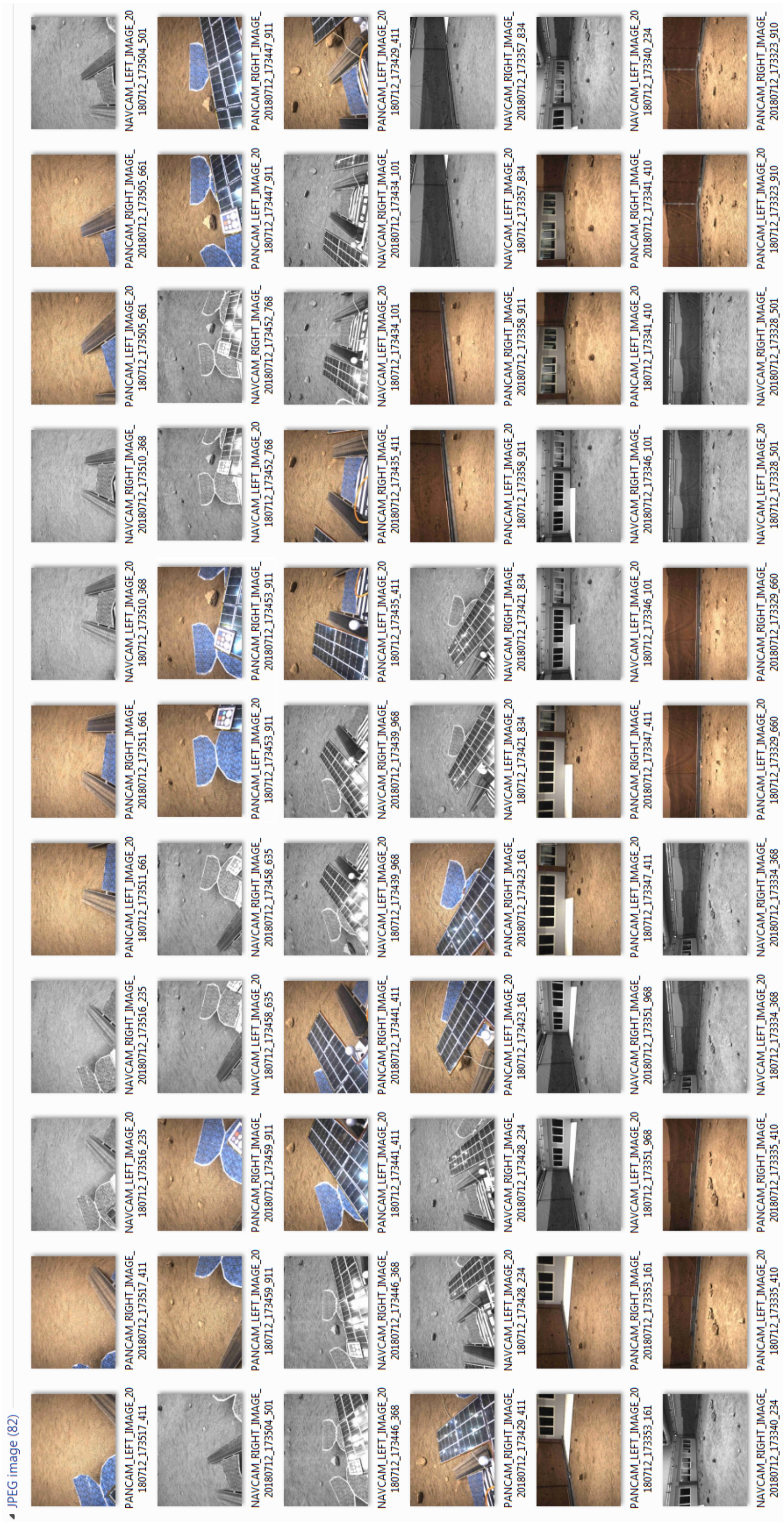
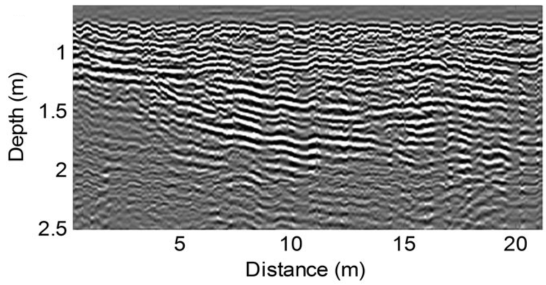


Figure 5.30: Folder containing output of JR Test 3, position A on-line session.

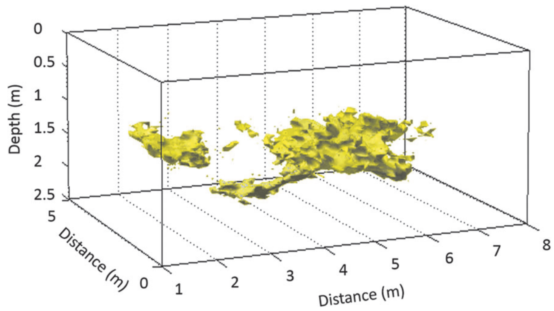
5.3 WISDOM grid tests

The search for life on Mars is one of the main targets of the ExoMars 2020 Rover mission. The evidence of life is more likely found underground, where the organic molecules are shielded by destructive agents such as radiation or oxidizing atmosphere.

The Water Ice Subsurface Deposit Observation on Mars (WISDOM) is a ground-penetrating radar that has the ability to investigate the subsoil and identify life presence. This antenna can provide information up to 10 m deep, in particular on the distribution and the state of the water. These data offer relevant clues for life search, as well as identifying the optimal drilling sites for sampling. The WISDOM also aims at finding the hazards that the drill could encounter in the first two meters of substrate.



(a) 2D radargram revealing layered deposits (Etna in Italy).



(b) 3D reconstruction of an underground ice layer (ice caves in Dachstein).

Figure 5.31: WISDOM sounding output (Credit: [6] *Valérie Ciarletti et al. "The WISDOM Radar: Unveiling the Subsurface Beneath the ExoMars Rover and Identifying the Best Locations for Drilling"*).

WISDOM is able to create 2D profiles (see Figure 5.31(a)) of the subsurface along the Rover traverse. A 3D reconstruction (see Figure 5.31(b)) can be generated by continuous sounding, with the Rover advancing at 20 m/h, or if the distances between successive soundings are reduced. In the latter case the Rover can carry out a WISDOM grid.

In Figure 5.32 ExoTeR footprints manifest the grid. During a WISDOM sounding the Rover follows a winding path, covering a 5 $m \times 5$ m area, and scans the subsoil every 10 cm to reconstruct a sub-superficial model, aiming at identifying the best drilling point.

During these soundings potential sampling sites are identified and evaluated. The ExoMars Rover must demonstrate the ability to return to an already visited site for the drilling.

The exact estimation of the Rover position on Mars has its difficulties, in fact there are no global positioning systems analogous to terrestrial GPS. During tests with ExoTeR it has been verified that the wheel-odometry, which uses the encoders, has high uncertainties due to the slippage of the wheels on sandy surfaces. The IMU, in the case of slow dynamics, presents non-tolerable drifts for an accurate estimate of the attitude. A complementary

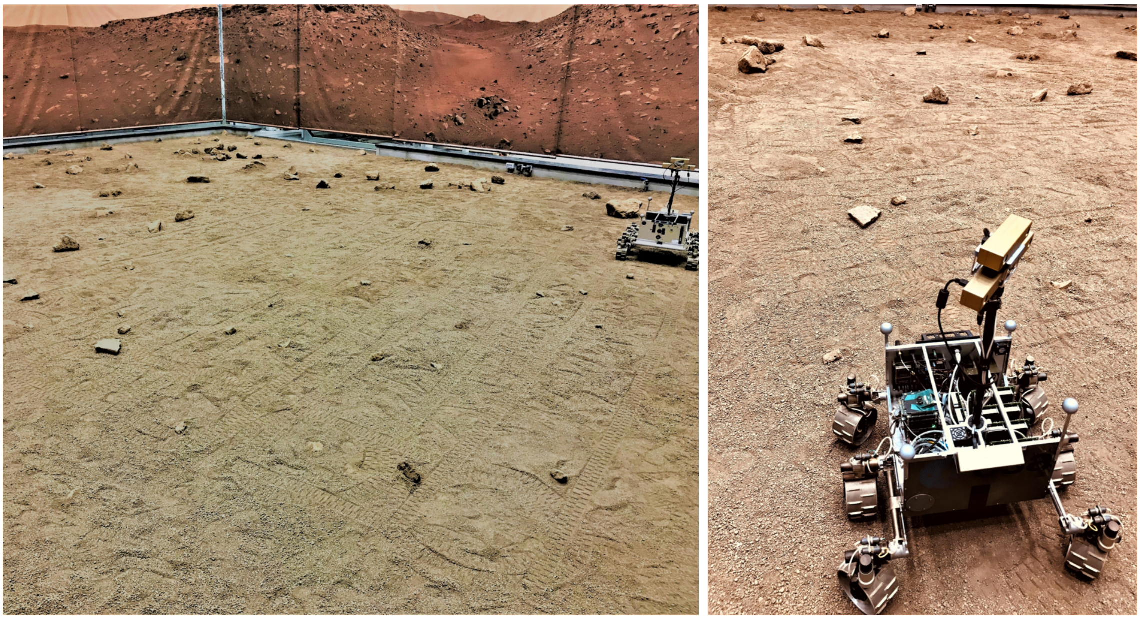


Figure 5.32: ExoTeR at the end and during a WISDOM sounding (Credit: Altec).

usable method is the stereo visual-odometry. This camera-based motion estimation system has proven to be reliable and accurate with the MER missions of NASA.

The WISDOM grid tests carried out in MTS, have proved visual-odometry algorithm performances. A very large dataset of images has been acquired to support the activities of our colleague Sebastiano Chiodini, from the University of Padova/CISAS, in the development of the WIRL (WISDOM grid Relative Localization) Algorithm, based on the stereo visual-odometry. The WIRL Algorithm reconstructs the Rover position and attitude (roll, pitch and heading angles) along the grid map followed during the WISDOM sounding.

WISDOM requires an accuracy of the Rover attitude inferior to 1°, and of the Rover position inferior to 20 *mm* in the *xy* plane. The WIRL Algorithm aims at this precision.

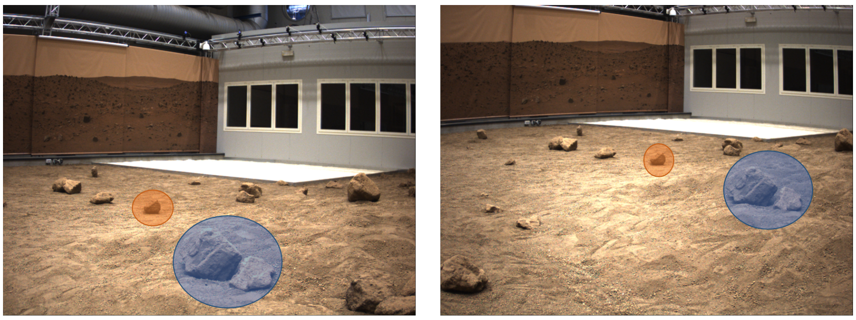


Figure 5.33: Rocks matching between subsequent images.

During the WISDOM sounding PanCam and NavCam acquire images. Captured stereo pairs are processed and, knowing the camera intrinsic and extrinsic parameters, a 3D point cloud of the camera view is generated with triangulation. By overlapping two subsequent 3D point clouds it is possible to reconstruct the path travelled. Each motion step is combined to obtain the whole trajectory.

Rocks or outcrops which is possible to see in two adjacent images are selected (see Figure 5.33). From these images it is possible to understand that the Rover is moving away from the boulder field. The WIRL algorithm would determine the trajectory followed.

Four types of tests have been performed:

- Test 1: camera intrinsic parameters calibration;
- Test 2: camera extrinsic parameters calibration;
- Test 3: WISDOM grid execution;
- Test 4: sunset condition.

A total of 3514 images have been acquired, i.e. 1757 stereo pairs.

5.3.1 Test 1: calibration of intrinsic camera parameters

In this test, the intrinsic calibration of NavCam and PanCam is performed.

ExoTeR takes several pictures of a patterned target with known dimensions. The Rover acquires stereo pair images with different Pan and Tilt camera orientations and from two different positions. These images are processed with Matlab® to calibrate the camera intrinsic parameters, see Figure 5.34. The more images are acquired, the better the calibration will be.

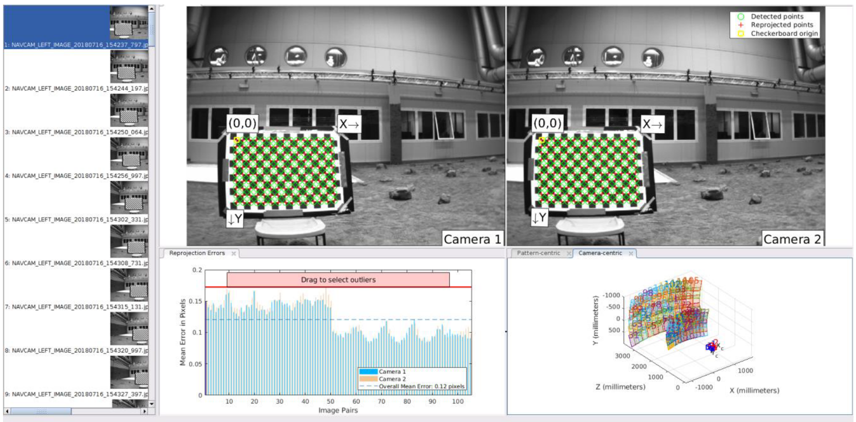
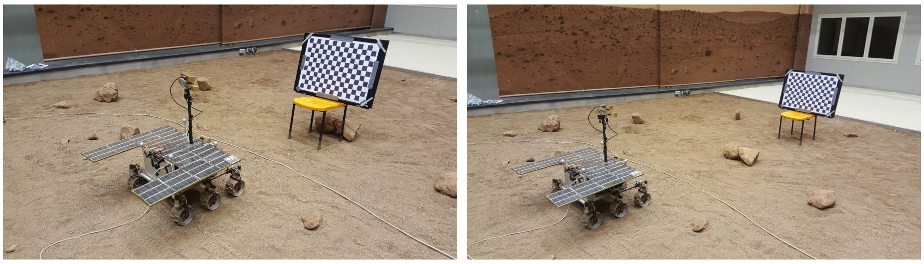


Figure 5.34: Calibration process, using Matlab (Credit: Sebastiano Chiodini).

ExoTeR is steady on the ground, when facing the target. During the test it occupies two different positions with respect to the target, shown in Figure 5.35.



(a) Position A. (b) Position B.

Figure 5.35: WISDOM Test 1 - ExoTer positions (Credit: ALTEC).

Position	Mast-target distance	Target orientation
A	1.88 m	Landscape
B	3.70 m	Landscape

Table 5.5: WISDOM Test 1 - Approximated ExoTer positions.

Table 5.5 reports the Rover positions tracked by OptiTrack:Motive.

NavCam, immediately followed by PanCam, captures 55 stereo pairs with PTU orientations in the order denoted in Table 5.6.

Pan → Tilt ↓ Pos. A	Pos. B	-20°	-16°	-12°	-8°	-4°	0°	4°	8°	12°	16°	20°
0°	-6°	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}			$\cdots$		11^{th}
6°	0°	12^{th}		$\cdots$			17^{th}			$\cdots$		22^{nd}
12°	6°	23^{rd}		$\cdots$			28^{th}			$\cdots$		33^{rd}
18°	12°	34^{th}		$\cdots$			39^{th}			$\cdots$		44^{th}
24°	18°	45^{th}		$\cdots$			50^{th}			$\cdots$		55^{th}

Table 5.6: WISDOM Test 1 - Order of the captures with Pan and Tilt of the camera.

Each capture produces 4 images. It requires the Mast orientation and the acquisition of stereo images (left and right) by the NavCam first and by the PanCam afterwards. Tilt values change from a position to the other so that the corresponding angles result in a good capture of the target.

This sequence is explicitly outlined in the Activity Plan B.4 and in the Activity Plan B.5 in Appendix B. These APs use the following commands:

```
MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s]);
NAVCAM_ACQ (0, type of the acquisition: 5=stereo, 0);
```

`PANCAM_ACQ (0, type of the acquisition: 5=stereo, 0).`

The AP executed in a given on-line session produces a folder. In each directory there are a TM and a TC text file and 220 images (55 stereo pairs from NavCam and 55 stereo pairs from PanCam).

Using the 440 acquired images, the intrinsic parameters of the cameras can be defined. These characterize the internal structure of the camera.

5.3.2 Test 2: calibration of extrinsic camera parameters

In this test, the extrinsic calibration of NavCam and PanCam is performed.

ExoTeR captures a stereo pair with NavCam and PanCam from 20 different positions around markers laying on the ground, see Figure 5.36. NavCam and PanCam keep the keep attitude for the whole test: Pan = 0° and Tilt = 20°.

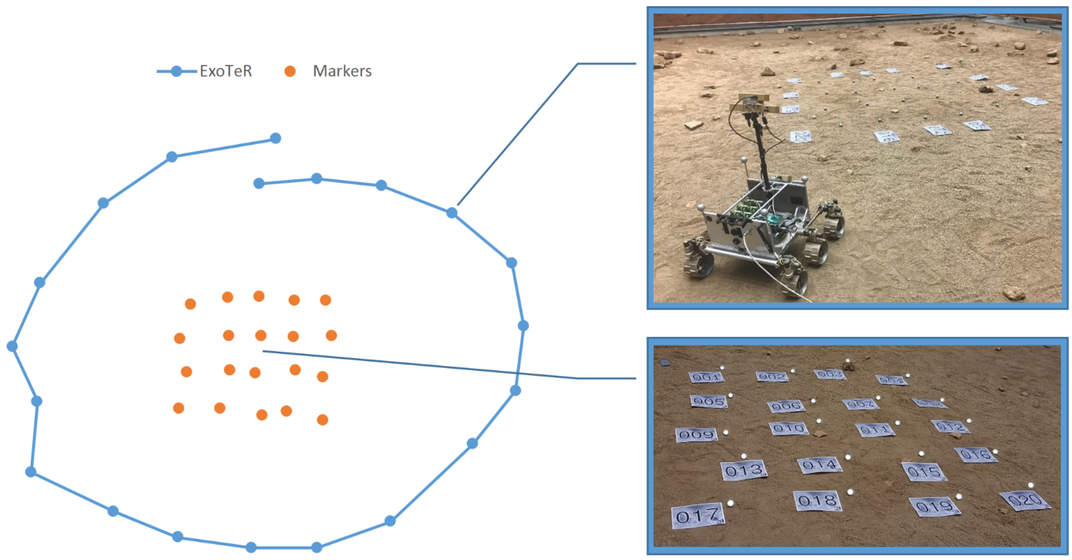


Figure 5.36: WISDOM Test 2 set-up (Credit: ALTEC).

The 20 markers are traced by OptiTrack:Motive to the positions relative to the MTS Arena origin (see Figure 5.28(a)) and indicated in Table 5.7.

ExoTeR is manually moved 20 times forming a circle around the markers. The Activity Plan B.6 outlined in Appendix B is launched 20 times. The 20 ExoTeR positions are shown in Figure 5.37 and reported in Table 5.8.

The AP executed in a given on-line session produces a folder for each ExoTeR position. In the directory there are a TM and a TC text file, and 4 images (a stereo pair from NavCam and a stereo pair from PanCam).

Marker	X	Y	Z	Marker	X	Y	Z
1	4.513	8.425	-0.002	11	5.742	9.768	0.018
2	4.625	9.102	0.018	12	5.71	10.504	0.001
3	4.531	9.712	0.098	13	6.132	8.374	0.003
4	4.692	10.357	-0.001	14	6.256	9.13	0.027
5	5.124	8.418	-0.003	15	6.237	9.757	0.015
6	5.281	9.134	0.009	16	6.249	10.429	0.008
7	5.256	9.782	0.022	17	6.677	8.205	0.012
8	5.245	10.482	-0.017	18	6.668	9.005	0.019
9	5.767	8.294	-0.006	19	6.798	9.773	0.013
10	5.652	9.079	0.008	20	6.715	10.44	0.003

Table 5.7: WISDOM Test 2 - Marker positions.

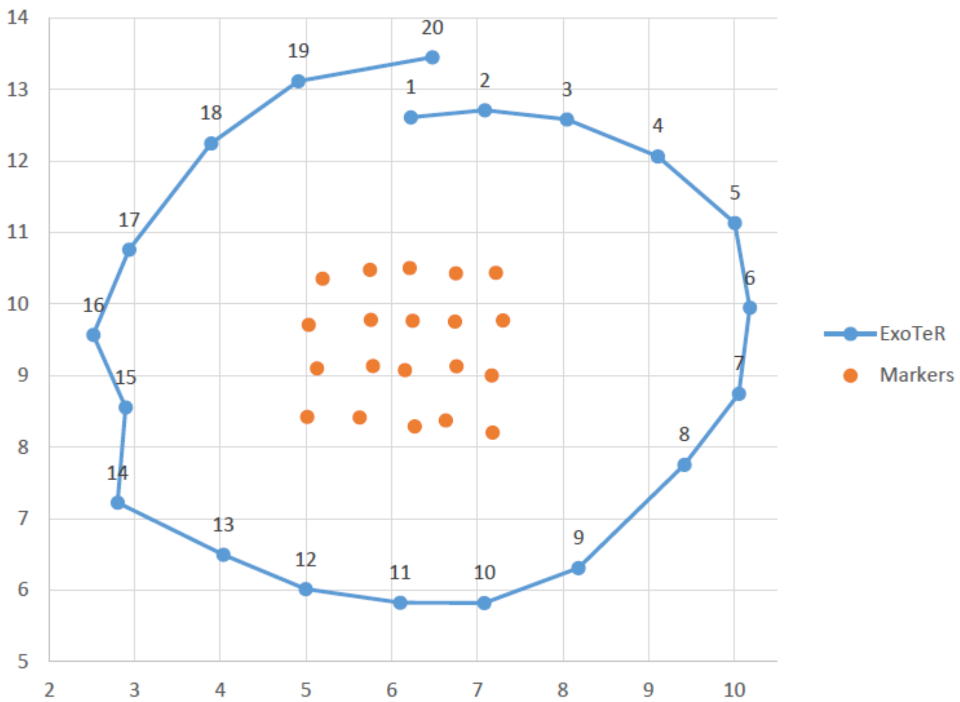


Figure 5.37: WISDOM Test 2 - ExoTer positions, data from OptiTrack:Motive.

Using the 80 images and knowing the pose of ExoTeR at acquisition, the extrinsic parameters of the cameras can be defined. These define the position of the camera with respect to the absolute MTS reference system.

Position	X	Y	Z	Yaw	Roll	Pitch
1	5.721	12.610	0.458	-85.8	-0.2	-1.3
2	6.588	12.709	0.437	-107.7	-0.4	0.3
3	7.547	12.582	0.440	-121.9	0.0	-1.0
4	8.608	12.065	0.446	-140.8	0.5	-1.6
5	9.508	11.133	0.456	-153.7	0.5	1.4
6	9.682	9.952	0.483	-173.1	0.4	1.2
7	9.556	8.749	0.539	166.7	4.8	3.8
8	8.919	7.756	0.563	149.7	8.0	0.7
9	7.682	6.310	0.466	131.1	4.6	-1.0
10	6.582	5.821	0.457	100.1	0.5	0.0
11	5.598	5.825	0.457	88.3	0.1	-1.7
12	4.494	6.017	0.449	72.0	0.9	0.6
13	3.534	6.498	0.476	56.8	0.5	-0.1
14	2.298	7.226	0.474	42.8	-0.9	-0.1
15	2.391	8.557	0.486	20.2	0.2	-0.4
16	2.014	9.570	0.477	-1.2	1.4	-0.9
17	2.433	10.760	0.471	-23.0	0.1	-0.5
18	3.390	12.248	0.462	-47.8	1.3	-0.6
19	4.408	13.114	0.470	-67.1	2.5	-1.7
20	5.974	13.451	0.445	-87.2	-0.4	-2.0

Table 5.8: WISDOM Test 2 - ExoTer positions, data from OptiTrack:Motive.

5.3.3 Test 3: WISDOM grid execution

In this test, ExoTeR follows an approaching path up to a WISDOM grid corner and then enters in the 5 $m \times 5$ m winding path. The Rover performs a panorama acquisition each meter, see Figure 5.38.

Atach meter along the grid path and along the approaching path the NavCam and the PanCam make a panoramic acquisition, capturing 16 stereo pairs with PTU orientations in the order denoted in Table 5.9.

Pan → Tilt ↓	$-235°$	$-190°$	$-145°$	$-100°$	$-55°$	$-10°$	$35°$	$50°$
10°	1st c.	2nd c.	3rd c.	4th c.	5th c.	6th c.	7th c.	8th c.
40°	9th c.	10th c.	11th c.	12th c.	13th c.	14th c.	15th c.	16th c.

Table 5.9: WISDOM Test 3 - Order of the captures (c.) with Pan and Tilt of the camera.

Each capture requires the Mast orientation (Pan from $-235°$ to $50°$, Tilt angles equal to

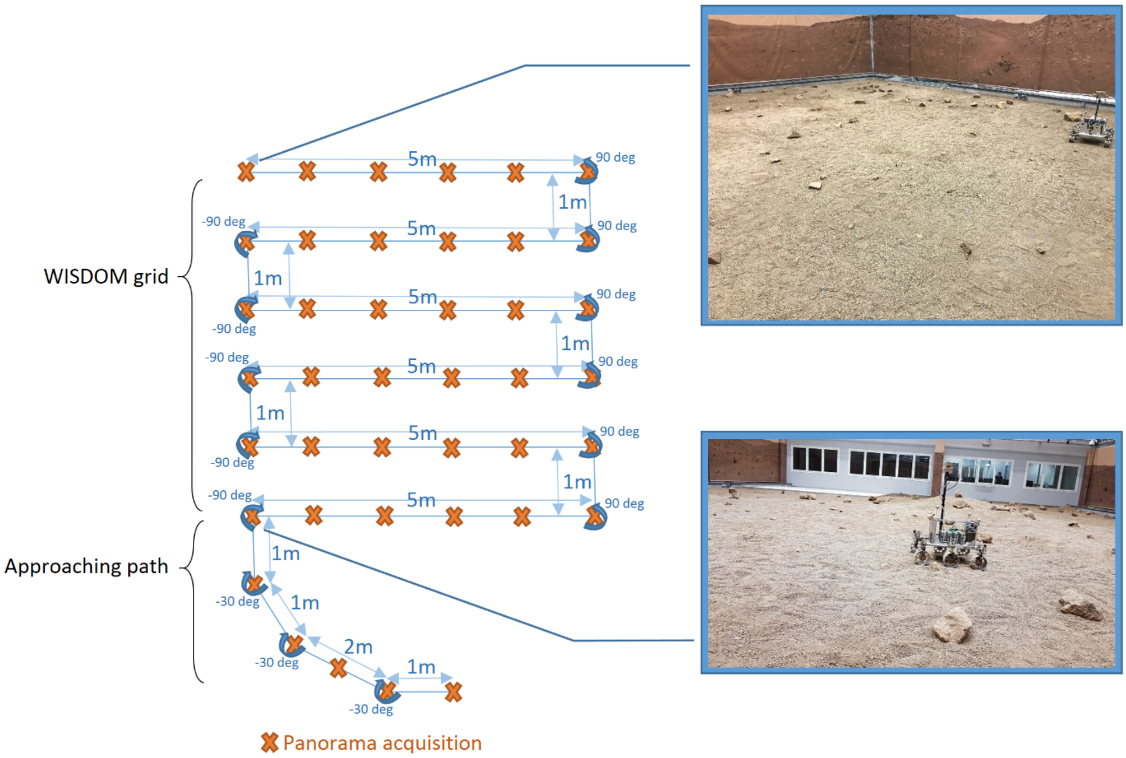


Figure 5.38: WISDOM Test 3 set-up (Credit: ALTEC).

20° and 10°) and the acquisition of 16 stereo pair images (left and right) by the NavCam first and by the PanCam afterwards.

Along the trajectory ExoTeR occupies 41 different positions, to make the panoramic acquisition. Figure 5.39 and Table 5.10 report ExoTeR positions tracked by OptiTrack:Motive. In the approaching path it goes forward for 1 m, makes a turnspot of $-30°$, goes forward for 2 m, makes a turnspot of $-30°$, goes forward for 1 m, makes a turnspot of $-30°$ and goes forward for 1 m. At this point ExoTeR begins the WISDOM grid path. It makes a turnspot of $-90°$, goes forward for 5 m, makes a turnspot of 90°, goes forward for 1 m, makes a turnspot of 90°, goes forward for 5 m, makes a turnspot of $-90°$ and goes forward for 1 m. This path is repeated until a square of 5 $m \times 5$ m is covered.

The Activity Plan B.7 in Appendix B, slightly different from the one used, shows which commands ExoTeR follows to keep on the desired path. This AP uses the following commands:

```
# PANORAMA
GNC_LLO (1, meters to be travelled, speed [m/s]);
GNC_TURNSPOT_GOTO (1, angle to turn, speed [deg/s], timeout [s]).
```

The panoramic acquisition is made every meter, and always before each turnspot. The acquisition sequence (`# PANORAMA`) is a list of additional commands specified in the Activity

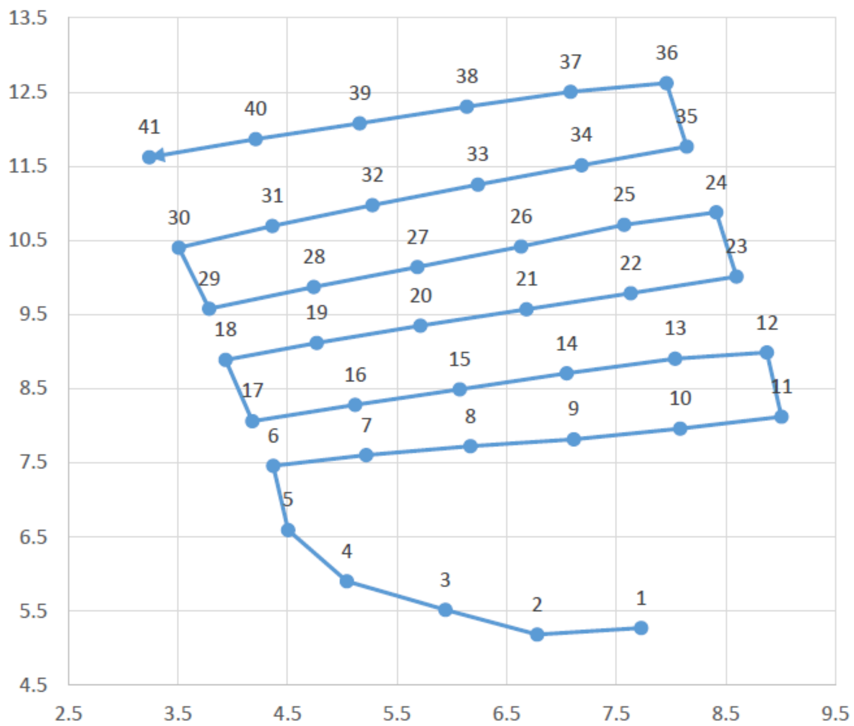


Figure 5.39: WISDOM Test 3 - ExoTer positions, data from OptiTrack:Motive.

Plan B.8 in Appendix B. It uses the following commands:

```
MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s]);
NAVCAM_ACQ (0, type of the acquisition: 5= stereo, 0);
PANCAM_ACQ (0, type of the acquisition: 5= stereo, 0).
```

ExoTeR takes about 3 hours to complete this trajectory, but its battery life is shorter than this. Dividing the AP into seven shorter APs gives the possibility of swapping the battery. At the end of each short AP the on-line session is closed, the corresponding folder is created, ExoTeR is switched off and the battery is changed. Every time ExoTeR is switched on, the GNC is updated with the latest data collected at the end of the previous session, and travel is re-started. In Figure 5.40 the approaching *path* is in light blue, the WISDOM grid is divided in 6 different parts (*grid1*, *grid2*, *grid3*, *grid4*, *grid5* and *grid6*). Each AP, except the last one, contains 6 panorama acquisitions. The *grid6* AP contains 5 panorama acquisitions.

In the on-line session folders of *path*, *grid1*, *grid2*, *grid3*, *grid4*, and *grid5* there are a TM and a TC text file, and 384 images (96 stereo pairs from NavCam and 96 stereo pairs from PanCam). In the *grid6* directory there are a TM and a TC text file, and 320 images (80 stereo pairs from NavCam and 80 stereo pairs from PanCam).

These 2624 images will be utilized by Chiodini (University of Padova) to recreate the

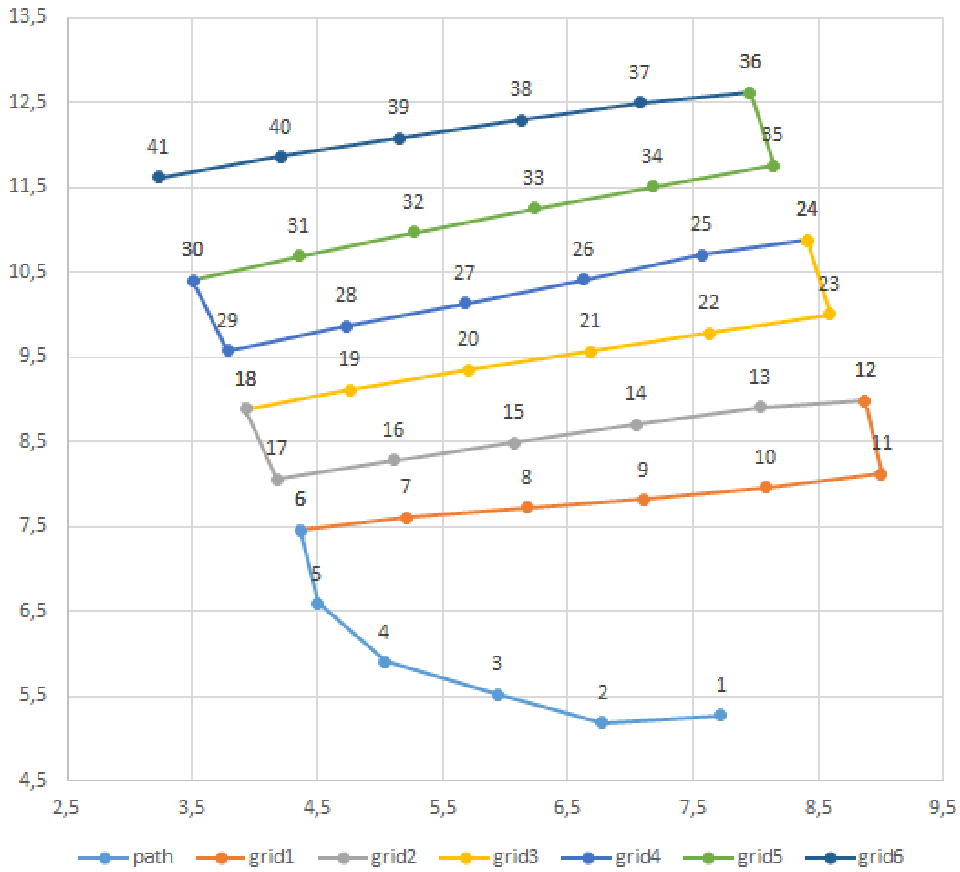


Figure 5.40: WISDOM Test 3 - The trajectory is divided in 7 APs.

trajectory followed by ExoTeR with the WIRL Algorithm, making use of the visual-odometry. The trajectory in output will be compared to the ExoTeR positions tracked by OptiTrack:Motive and to the one reported by the GNC TM. In Figure 5.41 it is possible to appreciate the difference between the positions covered by ExoTeR, tracked by OptiTrack:Motive, and those computed by the wheel-odometry and registered by the GNC of ExoTeR. The use of visual-odometry will allow the correction of the errors derived by the wheel-odometry. The Figure shows the direction of ExoTeR during the panorama acquisition. In the OptiTrack:Motive curve the Rover taking the images is represented by its body axes (x_B in red, y_B in blue), in the GNC curve the NavCam symbol displays the ExoTeR orientation.

Figure 5.42 shows ExoTeR at the end of the WISDOM grid. The Rover leaves footsteps where it passes, revealing the route travelled.

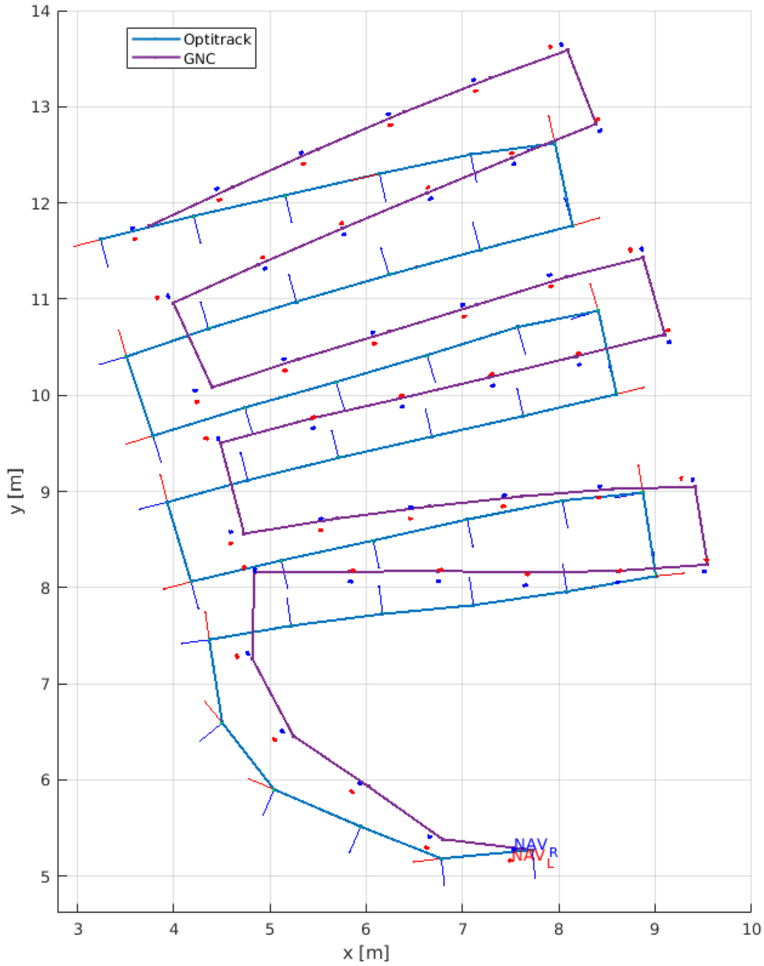


Figure 5.41: WISDOM Test 3 - ExoTeR positions tracked by OptiTrack:Motive and computed by the wheel-odometry (Credit: Sebastiano Chiodini).

Figure 5.42: WISDOM Test 3 - ExoTeR and the completed grid (Credit: ALTEC).

Position	X	Y	Z	Yaw	Roll	Pitch
1	7.727	5.271	0.462	-175	5	-4
2	6.779	5.183	0.451	-173	1	-2
3	5.941	5.515	0.439	157	1	-3
4	5.042	5.901	0.447	157	2	-3
5	4.505	6.59	0.451	129	-10	-1
6	4.368	7.458	0.458	98	1	-1
7	5.218	7.603	0.443	8	2	-3
8	6.169	7.725	0.448	7	2	-3
9	7.112	7.817	0.464	8	0	0
10	8.083	7.959	0.472	8	0	-2
11	9.008	8.119	0.516	6	-2	-6
12	8.876	8.986	0.467	100	4	-3
13	8.038	8.905	0.464	-169	1	-1
14	7.048	8.708	0.461	-168	3	-2
15	6.072	8.489	0.45	-168	3	-3
16	5.116	8.282	0.442	-167	1	-3
17	4.179	8.062	0.46	-165	0	-1
18	3.933	8.886	0.459	104	-9	-2
19	4.767	9.117	0.456	14	2	-1
20	5.713	9.349	0.459	14	2	-2
21	6.682	9.57	0.46	13	-8	-3
22	7.632	9.785	0.456	13	2	-3
23	8.598	10.011	0.457	14	3	-3
24	8.412	10.878	0.445	107	4	0
25	7.573	10.709	0.447	-164	2	0
26	6.631	10.417	0.447	-163	1	-2
27	5.686	10.139	0.462	-162	-10	-1
28	4.74	9.872	0.458	-163	-10	-1
29	3.784	9.577	0.461	-163	2	-3
30	3.508	10.401	0.461	106	3	-3
31	4.36	10.692	0.452	16	4	-3
32	5.275	10.973	0.425	16	1	-3
33	6.237	11.252	0.436	17	3	-3
34	7.183	11.513	0.423	15	2	-4
35	8.143	11.764	0.426	16	3	-2
36	7.96	12.621	0.414	103	2	-3
37	7.084	12.503	0.421	-168	2	-2
38	6.137	12.303	0.438	-167	0	-2
39	5.159	12.08	0.436	-167	2	-4
40	4.208	11.864	0.459	-166	1	-2
41	3.239	11.621	0.455	-165	1	-2

Table 5.10: WISDOM Test 3 - ExoTer positions, data from OptiTrack:Motive.

5.3.4 Test 4: sunset scenario

In this test the panorama acquisitions are performed in sunset condition. To simulate sunset light sources are reduced.

ExoTeR is placed approximately in the center of the trajectory executed in *Test 3: WISDOM grid execution* of Section 5.3.3. Table 5.11 reports the ExoTeR position tracked by OptiTrack:Motive. Five different conditions of reduced light are reproduced. A mobile illumination system is used in four of these cases (A, B, C and E), and some of the arena illumination LEDs over the gantry structure are used in one of them (D).

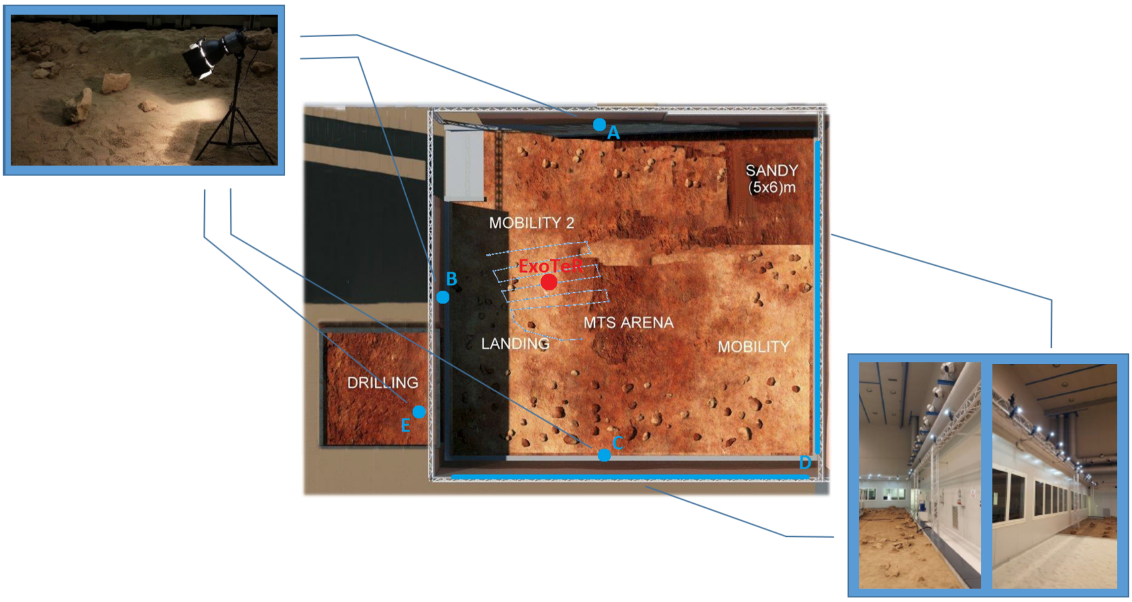


Figure 5.43: WISDOM Test 4 set-up (Credit: ALTEC).

X	Y	Z	Yaw	Roll	Pitch
5.735	9.513	0.46	-177	2	-4

Table 5.11: WISDOM Test 4 - ExoTer position, data from OptiTrack:Motive.

Figure 5.43 shows the test set-up and the position of the light sources.

Figure 5.44 shows:

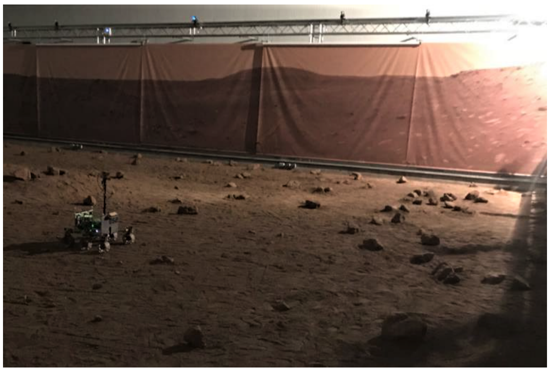
- In cases A, B, and C the mobile device is located inside the Arena focussing the light onto ExoTeR from three different positions, forming long shadows on the terrain.
- In case D a situation of extreme darkness is reproduced, with only half of the Main Arena LED lights on.

(a) Case A.

(b) Case B.

(c) Case C.

(d) Case D.



(e) Case E.

Figure 5.44: WISDOM Test 4 - light source cases (Credit: Altec).

- In case E the mobile device is located inside the Drilling facility, focussing the light down onto ExoTeR, producing shorter shadows on the terrain.

In each situation the NavCam and the PanCam make a panoramic acquisition, capturing 16 stereo pairs with PTU orientations in the order denoted in Table 5.12.

Pan → Tilt ↓	−235°	−190°	−145°	−100°	−55°	−10°	35°	50°
20°	1st c.	2nd c.	3rd c.	4th c.	5th c.	6th c.	7th c.	8th c.
10°	9th c.	10th c.	11th c.	12th c.	13th c.	14th c.	15th c.	16th c.

Table 5.12: WISDOM Test 4 - Order of the captures (c.) with Pan and Tilt of the camera.

Each capture requires the Mast orientation (Pan from -230 deg to 50 deg, Tilt angles equal to 20 deg and 10 deg) and the acquisition of stereo images (left and right) by the NavCam first and by the PanCam afterwards. The panoramic acquisition sequence is explicitly outlined in the Activity Plan B.9 in Appendix B. It uses the following commands:

```
MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s]);
NAVCAM_ACQ (0, type of the acquisition: 5= stereo, 0);
PANCAM_ACQ (0, type of the acquisition: 5= stereo, 0).
```

At each position the AP is launched in an on-line session. Every on-line session creates a folder with a TM and a TC text file, and 64 images (16 stereo pairs from NavCam and 16 stereo pairs from PanCam).

Using images acquired by the MTS we concluded that in reduced lighting conditions it is preferable that visual-odometry uses the footprints left by ExoTeR rather than the rocks. In Figure 5.45 it becomes clear that signs on the ground are more visible than the rocks.

(a) NavCam left image.

(b) NavCam right image.

(c) PanCam left image.

(d) PanCam right image.

Figure 5.45: Stereo pairs produced from ExoTeR in a capture, Case B.

5.3.5 Test 5: WISDOM grid in a single AP

In this last test the whole WISDOM grid is contained in a single AP, but only 5 NavCam panorama acquisitions are taken, in order to save battery life. Having produced a video of the whole test, a time-lapse of the entire WISDOM grid can be generated. The Rover performs the same trajectory executed in *Test 3: WISDOM grid execution* (see Section 5.3.3), and it does a panorama acquisition at the begin of approaching path and at each corner of the WISDOM grid, see Figure 5.46.

The reduced panorama acquisition sequence contains 5 stereo pair image captures with

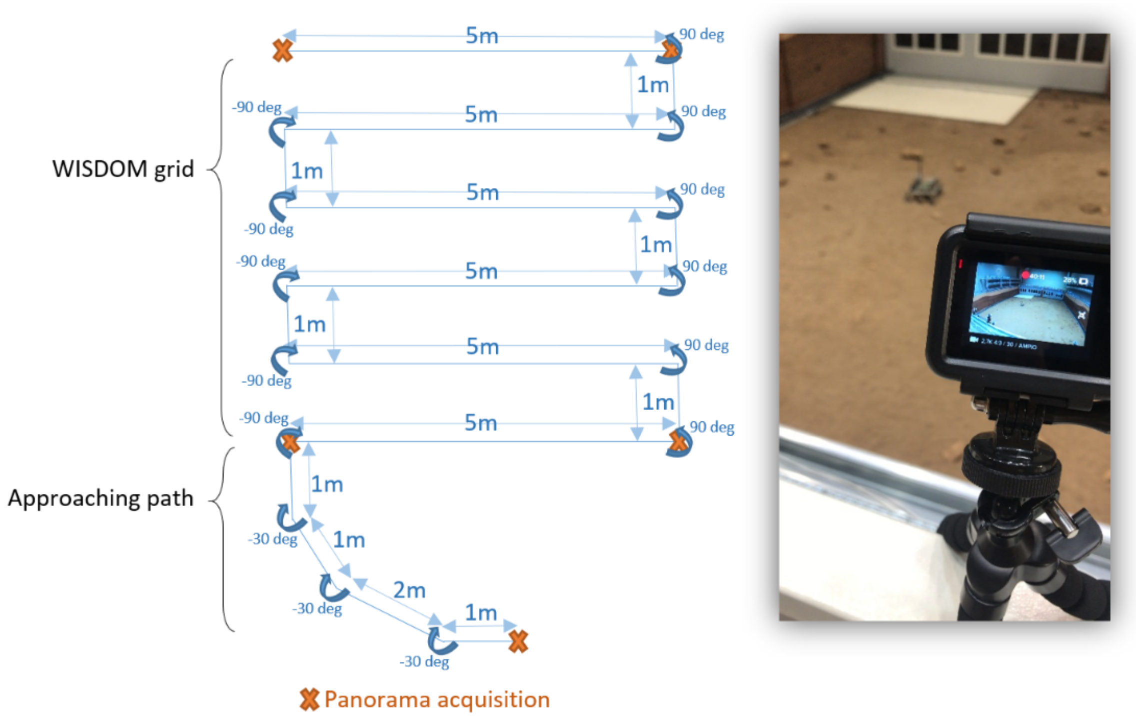


Figure 5.46: WISDOM Test 5 set-up (Credit: ALTEC).

PTU orientations in the order denoted in Table 5.13.

Pan → Tilt ↓	−235°	−175°	−115°	−55°	5°
20°	1st c.	2nd c.	3rd c.	4th c.	5th c.

Table 5.13: WISDOM Test 5 - Order of the captures (c.) with Pan and Tilt of the camera.

Each capture requires the Mast orientation (Pan from −235° to 5°, Tilt angles equal to 20°) and the acquisition of stereo images (left and right) by the NavCam.

The Activity Plan B.10, outlined in Appendix B, shows which commands ExoTeR follows in order to keep the desired path and to make the panoramic acquisition. This AP uses the following commands:

```
MAST_PTU_MoveTo (1, Pan [deg], Tilt [deg], timeout [s]);
NAVCAM_ACQ (0, type of the acquisition: 5= stereo, 0);
GNC_LLO (1, meter to be travelled, speed [m/s]);
GNC_TURNSPOT_GOTO (1, angle to turn, speed [deg/s], timeout [s]).
```

In this trajectory ExoTeR occupies 5 different positions, where it makes the panoramic acquisition. Figure 5.47 reports the ExoTeR trajectory tracked by OptiTrack:Motive, Table

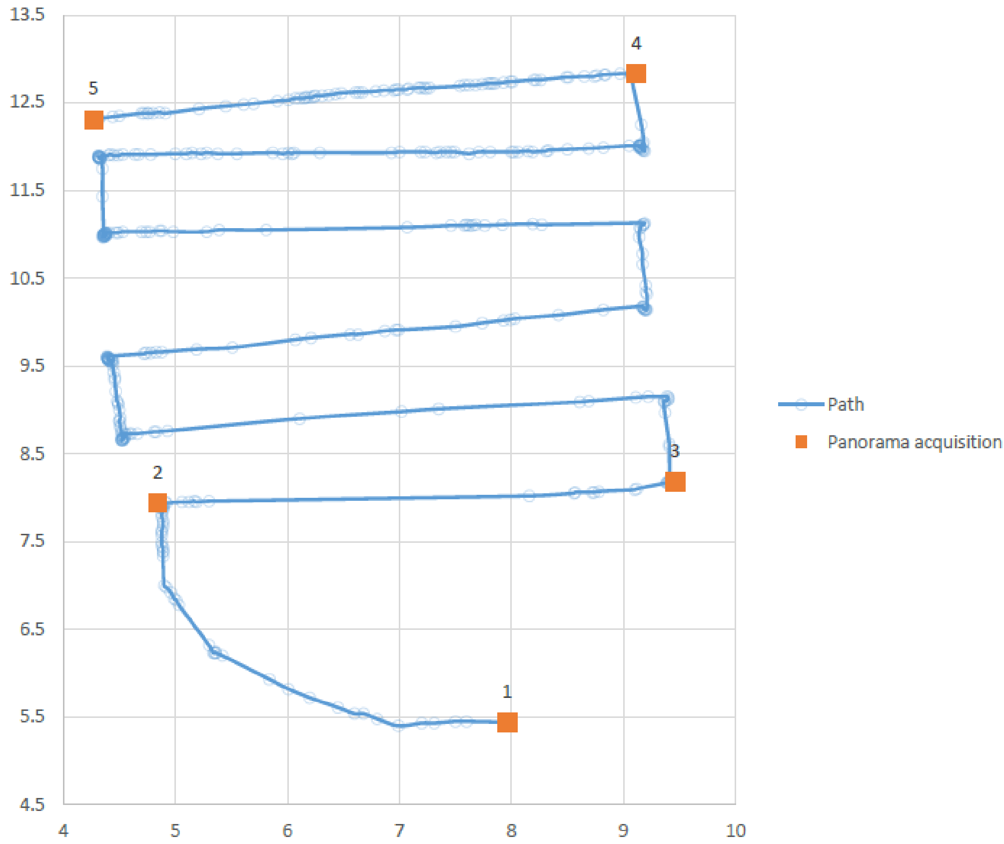


Figure 5.47: WISDOM Test 5 - ExoTer trajectory tracked by OptiTrack:Motive.

Panorama acquisition	X	Y	Z	Yaw	Roll	Pitch
1	7.96	5.44	0.52	-178.00	6.00	-1.00
2	4.84	7.94	0.47	2.00	2.00	1.00
3	9.46	8.18	0.59	-2.00	-11.00	-9.00
4	9.11	12.83	0.45	-175.00	1.00	0.00
5	4.27	12.31	0.47	-172.00	1.00	1.00

Table 5.14: WISDOM Test 5 - ExoTeR positions during the panorama acquisitions, data from OptiTrack:Motive.

5.14 specifies the 5 different positions occupied by ExoTeR during the panorama acquisitions.

The pitch of the 3rd panorama reveals that ExoTeR is on the hill of the MTS. Observing the positions occupied by ExoTeR near this acquisition we note that ExoTeR slides down the hill (see Figure 5.47). This is an example of the wheel-odometry generating an error: even if the wheel moves in the x direction, the Rover slips downwards, increasing the y position.

This error can be corrected by the comparison with the visual-odometry computation.

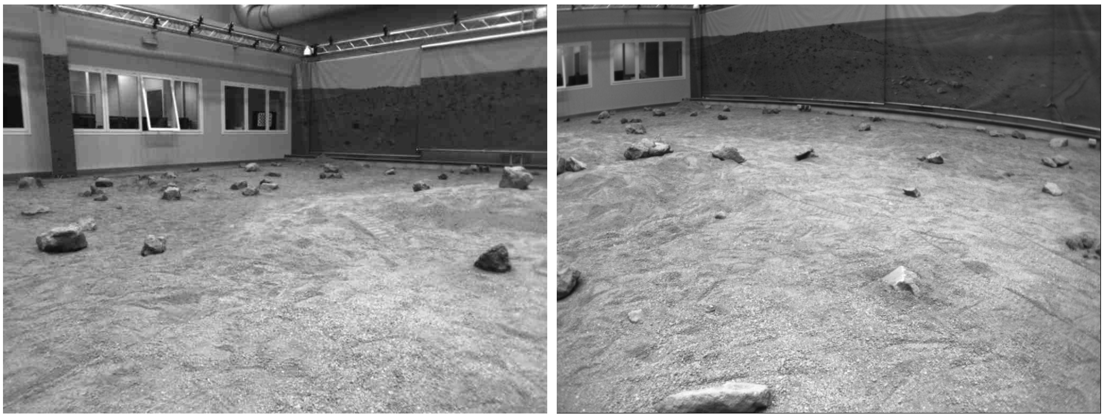
The execution of the AP in an on-line session generates a folder containing 50 images (25 stereo pairs from NavCam), a TCs and a TM of the session.

5.4 Issues occurred

Rectified and Compressed images

During the *Johanneum Research tests* described in Section 5.2 the PanCam team asked us the chance of capturing lossless images. ExoTeR saves compressed images and the pictures we receive in 3DROCS are already rectified. These outputs occupy less computer memory, and we can recognize the areas photographed as in a picture taken from a standard camera.

We decided to use uncompressed pictures, using all the data acquired by the camera, and we obtained un-rectified pictures, with raw distortion. Since the acquired images were used for calibration, it was important to obtain pristine images.



(a) Compressed and rectified image. (b) Un-compressed and un-rectified image.

Figure 5.48: ExoTeR output comparison.

Figure 5.48 compares a compressed and rectified image, with an uncompressed and un-rectified one. The latter is distorted, as taken with a fish-eye.

Mast un-deployed

During *Test 5: WISDOM grid in a single AP*, Section 5.3.5, an issue occurred: when ExoTeR was switched on, the `Deploy_Mast` command was not sent, hence not executed. Therefore all the NavCam acquisitions did not record the right camera orientation.

Pan and Tilt reported in image metadata are representative of a NavCam mounted on the stowed Mast. Tilt is always considered in the null value and Pan is the inverse of the yaw Rover value.

PTU lost of precision

At the end of the test campaigns carried out for the PanCam team and for Chiodini (University of Padova) and his WIRL Algorithm, an internal campaign of RSM in blind mode was planned.

This was interrupted because we noticed that the visualization of the DEMs generated by different cameras showed some mismatches. See for example Figure 5.49, comparing LocCam and PanCam DEMs.

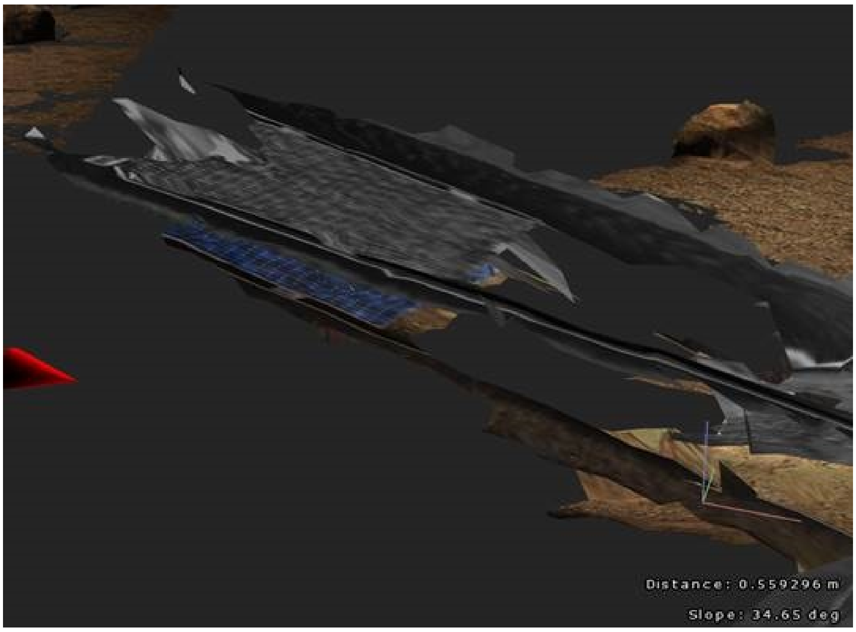


Figure 5.49: LocCam and PanCam DEM mismatches.

Recalibrating the PTU-null-position helped minimize this error. Achieving perfect alignment is difficult, but ExoTeR can do better than what the Figure show. In September 2018 recalibration of the PTU was performed, preparing the Rover for the blind-mode test which will be performed in November 2018.

Chapter 6

Conclusions and future work

The use of ExoTeR and 3DROCS software allowed us to realize the implications of operating remotely with Rover, highlighting complications that might arise.

Communications are limited and performed only at pre-established times. A list of activities, commanded by operators and run by the Rover, cannot be changed or stopped after it is launched. This operative mode requires a great deal of effort from the operators. They have to create the list of actions, based on data just received and whose evaluation has limited time.

Defining the work shifts of the operators is challenging. It will be very difficult to reach a definitive pattern of shifts, and week after week it will be necessary to check their effectiveness and validate them. Depending on the criticality of the mission phase, it is possible to preventively decide whether to work Mars Time or Earth Time. Afterwards, important issues not considered, that may arise with the mission in progress, must be highlighted, and issues previously overrated, must be downgraded. Working Earth Time is more sustainable and would guarantee a better working quality for the operator, but the scientific goals certainly benefit from working Mars Time. It will be necessary to request flexibility from the operators, aware of the cons of a Martian robotic mission. The pros of a satisfying job, result of gratifying scientific achievements, wont be negligible, anyway.

Wrapping up conclusion of test campaigns we need to define the amount of TM data, and images sufficient to evaluate the conditions of the Rover in the time available. It is necessary to ensure that we are able to create an Activity Plan within the period of time between communications with the TGO.

We need to define a check-list for decision making, reducing errors. The points of this check-list must be built on the basis of tests performed in MTS, where difficult and non-nominal situations are recreated. Bringing Rover's capabilities to the limits makes it possible to obtain operator relevant skills quickly.

A tool that implements the check-list independently could be created, as further work.

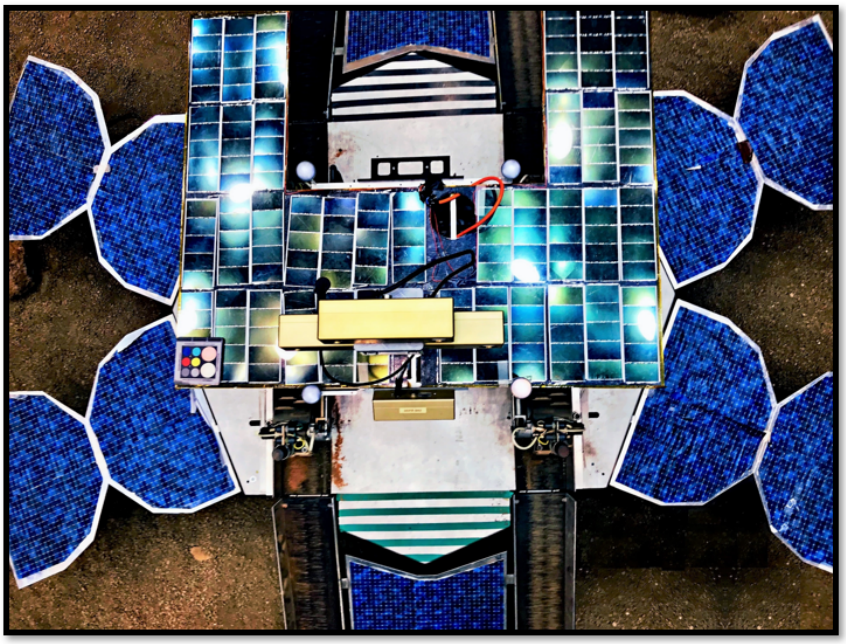
This would be accomplished by validated and trusted SW functions. For example, the slope estimation was reliable in tests performed and this could be automated.

An additional tool could guide the operator step-by-step into any typical SOL, during the tactical planning. This tool, customized for each user role, could highlight the completed operations, the action in progress, and those yet to be performed. It would show the time available between different deadlines. It could also contain information about operations performed in parallel by other operators.

The ROCC validation phase will begin in late 2018, and the MTS facility will take part to it. This phase consists of a set of integrated tests.

An important test which will take place in MTS in November 2018, aims at experiencing all the RSM phases in blind mode. PLTE, Egress, Rover Commissioning and Driving phases will be executed by ExoTeR, following APs produced by operators unaware of the Rover status in MTS. In these tests it will be crucial to take into account the limited energy and resources of the Rover in a working day. The timing will be dictated by the bandwidth and the communication slots with the TGO, simulated.

The test starts after successful landing and LP subsystems deployment.
The first operation which the Rover is asked to execute is the Rover Check-out, starting with the verification of elements supporting the RM stand-up and Egress. This test phase aims at understanding some non-apparent complexities of the communication chain.
The second test phase exercises on the Egress. This manoeuvre is considered to be the most critical operation of the entire lifetime of a Rover, and operators need to be secure and confident to use products downlinked from the Rover.



Once the Rover has completed the Egress from the LP, the RM functional commissioning operations start. It is possible to make use of the unique moment when RM and LP can take images of each other on the Martian soil. It is worth noting that the Rover Module circumnavigates the Surface Platform allowing mutual Rover and LP imaging. In this phase it is important to align the lander camera shooting with the rover positioning.
The RM must be moved away from the landing site in order to guarantee that the first opening of the ALD will occur in an area not contaminated by the Landing Platform engines.

During the driving test phase it is possible to experience the traverse with WISDOM. It is expected that the Rover follows its trajectory, then it stops for the specified time and it resumes the trajectory execution after scanning. During the test the distance between stops (from 10cm to several m), the duration of these stops (from 0s to 30s) and the time-out for the execution will be defined.

A wide number of simulation campaigns will ensure the readiness of processes and procedures to be utilized during ExoMars mission. In addition, it will provide the right level of confidence and training to the ROCC team, ensuring a smooth RSM.

Appendix A

Acronyms/Abbreviations

A

- **ADE** Actuator Drive Electronics
- **AER** Azimuth, Elevation and Range
- **ALD** Analytical Laboratory Drawer
- **AP** Activity Plan

C

- **CEDL** Coast, Entry, Descent and Landing
- **CLUPI** Close-Up Imager
- **CL** Central Left
- **CM** Carrier Module
- **CR** Central Right

D

- **DEM** Digital Elevation Model
- **DM** Descent Module
- **DSA** Deep Space Antenna

E

- **EAT** Event/Action Table
- **E.C.** Experiment Cycle
- **EDL** Entry, Descent and Landing
- **ERF** Execution Returned Flag
- **ERV** Execution Returned Value
- **ESA** European Space Agency
- **ESOC** European Space Operations Centre
- **ExoTeR** ExoMars Testing Rover

F

- **FD** Flight Director
- **FL** Front Left
- **FR** Front Right

G

- **GNC** Guidance, Navigation, and Control
- **GTM** Ground Test Model

H

- **HK** HouseKeeping
- **HW** Hardware

I

- **IMU** Inertial Measurement Unit
- **IR** Infrared

- **ISEM** Infrared Spectrometer for ExoMars

L

- **LEOP** Launch and Early Orbital Phase
- **LocCam** Localisation cameras
- **LP** Landing Platform
- **LTST** Local True Solar Time

M

- **MER** Mars Exploration Rover
- **MMS** Mission Management Software
- **MOMA** Martian Organic Molecule Analyzer
- **MOC** Mission Operation Centre
- **MSL** Mars Science Laboratory
- **MTS** Mars Terrain Simulator

N

- **NavCam** Navigation cameras

O

- **OBC** On-Board Computer

P

- **PLTE** Post Landing To Egress
- **PPL** Pasteur Payload
- **PTU** Pan & Tilt Unit

R

- **RAPDL** Rover Activity Plan Description Language
- **RET** Rover Engineering Team
- **RGST** ROCC Ground Support Team
- **RL** Rear Left
- **RLS** Raman Laser Spectrometer
- **RM** Rover Module
- **ROCC** Rover Operations Control Centre
- **ROM** Rover Operations Manager
- **ROSET** ROCC System Sustaining Engineering Team
- **RPT** Rover Planners Team
- **RR** Rear Right
- **RSET** Rover Sustaining Engineering Team
- **RSM** Rover Surface Mission

S

- **SDMT** Science Data Management Team
- **SOC** Science Operation Centre
- **SOST** Science Operations Support Team
- **SOWG** Science Operations Working Group
- **SP** Surface Platform
- **SPDS** Sample Preparation and Distribution System
- **SPOCC** Surface Platform Operations Control Centre
- **STL** Scientists Team Lead
- **SW** Software
- **S/S** Subsystem

T

- **TASI** Thales Alenia Space - Italia
- **TBD** To be defined
- **TC** Telecommand
- **TGO** Trace Gas Orbiter
- **TM** Telemetry

V

- **V.S.** Vertical Surveys

W

- **WISDOM** Water Ice and Subsurface Deposit Observations on Mars

Appendix B

APs full text

Johanneum Research (JR) tests

Test 1: NavCam and PanCam calibration.

```
EXEC Activity#1,        MAST_PTU_MoveTo (1,20.00,-15,1000);
EXEC Activity#2,        NAVCAM_ACQ (0,5,0);
EXEC Activity#3,        PANCAM_ACQ (0,5,0);
EXEC Activity#4,        MAST_PTU_MoveTo (1,10.00,-15,1000);
EXEC Activity#5,        NAVCAM_ACQ (0,5,0);
EXEC Activity#6,        PANCAM_ACQ (0,5,0);
EXEC Activity#7,        MAST_PTU_MoveTo (1,0.00,-15,1000);
EXEC Activity#8,        NAVCAM_ACQ (0,5,0);
EXEC Activity#9,        PANCAM_ACQ (0,5,0);
EXEC Activity#10,       MAST_PTU_MoveTo (1,-10.00,-15,1000);
EXEC Activity#11,       NAVCAM_ACQ (0,5,0);
EXEC Activity#12,       PANCAM_ACQ (0,5,0);
EXEC Activity#13,       MAST_PTU_MoveTo (1,-20.00,-15,1000);
EXEC Activity#14,       NAVCAM_ACQ (0,5,0);
EXEC Activity#15,       PANCAM_ACQ (0,5,0);

EXEC Activity#16,       MAST_PTU_MoveTo (1,20.00,-9,1000);
EXEC Activity#17,       NAVCAM_ACQ (0,5,0);
EXEC Activity#18,       PANCAM_ACQ (0,5,0);
EXEC Activity#19,       MAST_PTU_MoveTo (1,10.00,-9,1000);
EXEC Activity#20,       NAVCAM_ACQ (0,5,0);
EXEC Activity#21,       PANCAM_ACQ (0,5,0);
EXEC Activity#22,       MAST_PTU_MoveTo (1,0.00,-9,1000);
EXEC Activity#23,       NAVCAM_ACQ (0,5,0);
EXEC Activity#24,       PANCAM_ACQ (0,5,0);
EXEC Activity#25,       MAST_PTU_MoveTo (1,-10.00,-9,1000);
EXEC Activity#26,       NAVCAM_ACQ (0,5,0);
EXEC Activity#27,       PANCAM_ACQ (0,5,0);
```

```
EXEC Activity#28,        MAST_PTU_MoveTo (1,-20.00,-9,1000);
EXEC Activity#29,        NAVCAM_ACQ (0,5,0);
EXEC Activity#30,        PANCAM_ACQ (0,5,0);

EXEC Activity#16,        MAST_PTU_MoveTo (1,20.00,-3,1000);
EXEC Activity#17,        NAVCAM_ACQ (0,5,0);
EXEC Activity#18,        PANCAM_ACQ (0,5,0);
EXEC Activity#19,        MAST_PTU_MoveTo (1,10.00,-3,1000);
EXEC Activity#20,        NAVCAM_ACQ (0,5,0);
EXEC Activity#21,        PANCAM_ACQ (0,5,0);
EXEC Activity#22,        MAST_PTU_MoveTo (1,0.00,-3,1000);
EXEC Activity#23,        NAVCAM_ACQ (0,5,0);
EXEC Activity#24,        PANCAM_ACQ (0,5,0);
EXEC Activity#25,        MAST_PTU_MoveTo (1,-10.00,-3,1000);
EXEC Activity#26,        NAVCAM_ACQ (0,5,0);
EXEC Activity#27,        PANCAM_ACQ (0,5,0);
EXEC Activity#28,        MAST_PTU_MoveTo (1,-20.00,-3,1000);
EXEC Activity#29,        NAVCAM_ACQ (0,5,0);
EXEC Activity#30,        PANCAM_ACQ (0,5,0);

EXEC Activity#46,        MAST_PTU_MoveTo (1,20.00,3,1000);
EXEC Activity#47,        NAVCAM_ACQ (0,5,0);
EXEC Activity#48,        PANCAM_ACQ (0,5,0);
EXEC Activity#49,        MAST_PTU_MoveTo (1,10.00,3,1000);
EXEC Activity#50,        NAVCAM_ACQ (0,5,0);
EXEC Activity#51,        PANCAM_ACQ (0,5,0);
EXEC Activity#52,        MAST_PTU_MoveTo (1,0.00,3,1000);
EXEC Activity#53,        NAVCAM_ACQ (0,5,0);
EXEC Activity#54,        PANCAM_ACQ (0,5,0);
EXEC Activity#55,        MAST_PTU_MoveTo (1,-10.00,3,1000);
EXEC Activity#56,        NAVCAM_ACQ (0,5,0);
EXEC Activity#57,        PANCAM_ACQ (0,5,0);
EXEC Activity#58,        MAST_PTU_MoveTo (1,-20.00,3,1000);
EXEC Activity#59,        NAVCAM_ACQ (0,5,0);
EXEC Activity#60,        PANCAM_ACQ (0,5,0);

EXEC Activity#61,        MAST_PTU_MoveTo (1,20.00,9,1000);
EXEC Activity#62,        NAVCAM_ACQ (0,5,0);
EXEC Activity#63,        PANCAM_ACQ (0,5,0);
EXEC Activity#64,        MAST_PTU_MoveTo (1,10.00,9,1000);
EXEC Activity#65,        NAVCAM_ACQ (0,5,0);
EXEC Activity#66,        PANCAM_ACQ (0,5,0);
EXEC Activity#67,        MAST_PTU_MoveTo (1,0.00,9,1000);
EXEC Activity#68,        NAVCAM_ACQ (0,5,0);
EXEC Activity#69,        PANCAM_ACQ (0,5,0);
EXEC Activity#70,        MAST_PTU_MoveTo (1,-10.00,9,1000);
EXEC Activity#71,        NAVCAM_ACQ (0,5,0);
EXEC Activity#72,        PANCAM_ACQ (0,5,0);
EXEC Activity#73,        MAST_PTU_MoveTo (1,-20.00,9,1000);
```

```
EXEC Activity#74,       NAVCAM_ACQ (0,5,0);
EXEC Activity#75,       PANCAM_ACQ (0,5,0);

EXEC Activity#76,       MAST_PTU_MoveTo (1,20.00,15,1000);
EXEC Activity#77,       NAVCAM_ACQ (0,5,0);
EXEC Activity#78,       PANCAM_ACQ (0,5,0);
EXEC Activity#79,       MAST_PTU_MoveTo (1,10.00,15,1000);
EXEC Activity#80,       NAVCAM_ACQ (0,5,0);
EXEC Activity#81,       PANCAM_ACQ (0,5,0);
EXEC Activity#82,       MAST_PTU_MoveTo (1,0.00,15,1000);
EXEC Activity#83,       NAVCAM_ACQ (0,5,0);
EXEC Activity#84,       PANCAM_ACQ (0,5,0);
EXEC Activity#85,       MAST_PTU_MoveTo (1,-10.00,15,1000);
EXEC Activity#86,       NAVCAM_ACQ (0,5,0);
EXEC Activity#87,       PANCAM_ACQ (0,5,0);
EXEC Activity#88,       MAST_PTU_MoveTo (1,-20.00,15,1000);
EXEC Activity#89,       NAVCAM_ACQ (0,5,0);
EXEC Activity#90,       PANCAM_ACQ (0,5,0);

END_SOL;
```

Activity Plan B.1: JR test 1: NavCam and PanCam calibration.

Test 2: LocCam calibration.

```
EXEC A1, NAVCAM_ACQ ( 0, 5, 0 ) ;
EXEC A2, LOCCAM_ACQ ( 0, 5, 0 ) ;

END_SOL;
```

Activity Plan B.2: JR test 2: LocCam calibration.

Test 3: panorama acquisitions.

```
EXEC    A0,     LOCCAM_ACQ(0,5,0);

EXEC    A1,     MAST_PTU_MoveTo(1,-230,10,100);
EXEC    A2,     NAVCAM_ACQ(0,5,0);
EXEC    A3,     PANCAM_ACQ(0,5,0);
EXEC    A4,     MAST_PTU_MoveTo(1,-200,10,100);
EXEC    A5,     NAVCAM_ACQ(0,5,0);
EXEC    A6,     PANCAM_ACQ(0,5,0);
EXEC    A7,     MAST_PTU_MoveTo(1,-170,10,100);
EXEC    A8,     NAVCAM_ACQ(0,5,0);
EXEC    A9,     PANCAM_ACQ(0,5,0);
EXEC    A10,    MAST_PTU_MoveTo(1,-140,10,100);
```

```
EXEC      A11,      NAVCAM_ACQ(0,5,0);
EXEC      A12,      PANCAM_ACQ(0,5,0);
EXEC      A13,      MAST_PTU_MoveTo(1,-110,10,100);
EXEC      A14,      NAVCAM_ACQ(0,5,0);
EXEC      A15,      PANCAM_ACQ(0,5,0);
EXEC      A16,      MAST_PTU_MoveTo(1,-80,10,100);
EXEC      A17,      NAVCAM_ACQ(0,5,0);
EXEC      A18,      PANCAM_ACQ(0,5,0);
EXEC      A19,      MAST_PTU_MoveTo(1,-50,10,100);
EXEC      A20,      NAVCAM_ACQ(0,5,0);
EXEC      A21,      PANCAM_ACQ(0,5,0);
EXEC      A22,      MAST_PTU_MoveTo(1,-20,10,100);
EXEC      A23,      NAVCAM_ACQ(0,5,0);
EXEC      A24,      PANCAM_ACQ(0,5,0);
EXEC      A25,      MAST_PTU_MoveTo(1,10,10,100);
EXEC      A26,      NAVCAM_ACQ(0,5,0);
EXEC      A27,      PANCAM_ACQ(0,5,0);
EXEC      A28,      MAST_PTU_MoveTo(1,40,10,100);
EXEC      A29,      NAVCAM_ACQ(0,5,0);
EXEC      A30,      PANCAM_ACQ(0,5,0);

EXEC      A31,      MAST_PTU_MoveTo(1,-230,40,100);
EXEC      A32,      NAVCAM_ACQ(0,5,0);
EXEC      A33,      PANCAM_ACQ(0,5,0);
EXEC      A34,      MAST_PTU_MoveTo(1,-200,40,100);
EXEC      A35,      NAVCAM_ACQ(0,5,0);
EXEC      A36,      PANCAM_ACQ(0,5,0);
EXEC      A37,      MAST_PTU_MoveTo(1,-170,40,100);
EXEC      A38,      NAVCAM_ACQ(0,5,0);
EXEC      A39,      PANCAM_ACQ(0,5,0);
EXEC      A40,      MAST_PTU_MoveTo(1,-140,40,100);
EXEC      A41,      NAVCAM_ACQ(0,5,0);
EXEC      A42,      PANCAM_ACQ(0,5,0);
EXEC      A43,      MAST_PTU_MoveTo(1,-110,40,100);
EXEC      A44,      NAVCAM_ACQ(0,5,0);
EXEC      A45,      PANCAM_ACQ(0,5,0);
EXEC      A46,      MAST_PTU_MoveTo(1,-80,40,100);
EXEC      A47,      NAVCAM_ACQ(0,5,0);
EXEC      A48,      PANCAM_ACQ(0,5,0);
EXEC      A49,      MAST_PTU_MoveTo(1,-50,40,100);
EXEC      A50,      NAVCAM_ACQ(0,5,0);
EXEC      A51,      PANCAM_ACQ(0,5,0);
EXEC      A52,      MAST_PTU_MoveTo(1,-20,40,100);
EXEC      A53,      NAVCAM_ACQ(0,5,0);
EXEC      A54,      PANCAM_ACQ(0,5,0);
EXEC      A55,      MAST_PTU_MoveTo(1,10,40,100);
EXEC      A56,      NAVCAM_ACQ(0,5,0);
EXEC      A57,      PANCAM_ACQ(0,5,0);
EXEC      A58,      MAST_PTU_MoveTo(1,40,40,100);
```

```
EXEC    A59,    NAVCAM_ACQ(0,5,0);
EXEC    A60,    PANCAM_ACQ(0,5,0);

END_SOL;
```

Activity Plan B.3: JR test 3: panorama acquisitions.

WISDOM grid tests

Test 1: calibration of intrinsic camera parameters.

Position A.

```
EXEC    Activity#1,     MAST_PTU_MoveTo(1,-20.00,0,1000);
EXEC    Activity#2,     NAVCAM_ACQ(0,5,0);
EXEC    Activity#3,     PANCAM_ACQ(0,5,0);
EXEC    Activity#4,     MAST_PTU_MoveTo(1,-16.00,0,1000);
EXEC    Activity#5,     NAVCAM_ACQ(0,5,0);
EXEC    Activity#6,     PANCAM_ACQ(0,5,0);
EXEC    Activity#7,     MAST_PTU_MoveTo(1,-12.00,0,1000);
EXEC    Activity#8,     NAVCAM_ACQ(0,5,0);
EXEC    Activity#9,     PANCAM_ACQ(0,5,0);
EXEC    Activity#10,    MAST_PTU_MoveTo(1,-8.00,0,1000);
EXEC    Activity#11,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#12,    PANCAM_ACQ(0,5,0);
EXEC    Activity#13,    MAST_PTU_MoveTo(1,-4.00,0,1000);
EXEC    Activity#14,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#15,    PANCAM_ACQ(0,5,0);
EXEC    Activity#16,    MAST_PTU_MoveTo(1,0.00,0,1000);
EXEC    Activity#17,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#18,    PANCAM_ACQ(0,5,0);
EXEC    Activity#19,    MAST_PTU_MoveTo(1,4.00,0,1000);
EXEC    Activity#20,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#21,    PANCAM_ACQ(0,5,0);
EXEC    Activity#22,    MAST_PTU_MoveTo(1,8.00,0,1000);
EXEC    Activity#23,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#24,    PANCAM_ACQ(0,5,0);
EXEC    Activity#25,    MAST_PTU_MoveTo(1,12.00,0,1000);
EXEC    Activity#26,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#27,    PANCAM_ACQ(0,5,0);
EXEC    Activity#28,    MAST_PTU_MoveTo(1,16.00,0,1000);
EXEC    Activity#29,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#30,    PANCAM_ACQ(0,5,0);
EXEC    Activity#31,    MAST_PTU_MoveTo(1,20.00,0,1000);
EXEC    Activity#32,    NAVCAM_ACQ(0,5,0);
EXEC    Activity#33,    PANCAM_ACQ(0,5,0);

```

```
EXEC     Activity#34,     MAST_PTU_MoveTo(1,-20.00,6,1000);
EXEC     Activity#35,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#36,     PANCAM_ACQ(0,5,0);
EXEC     Activity#37,     MAST_PTU_MoveTo(1,-16.00,6,1000);
EXEC     Activity#38,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#39,     PANCAM_ACQ(0,5,0);
EXEC     Activity#40,     MAST_PTU_MoveTo(1,-12.00,6,1000);
EXEC     Activity#41,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#42,     PANCAM_ACQ(0,5,0);
EXEC     Activity#43,     MAST_PTU_MoveTo(1,-8.00,6,1000);
EXEC     Activity#44,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#45,     PANCAM_ACQ(0,5,0);
EXEC     Activity#46,     MAST_PTU_MoveTo(1,-4.00,6,1000);
EXEC     Activity#47,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#48,     PANCAM_ACQ(0,5,0);
EXEC     Activity#49,     MAST_PTU_MoveTo(1,0.00,6,1000);
EXEC     Activity#50,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#51,     PANCAM_ACQ(0,5,0);
EXEC     Activity#52,     MAST_PTU_MoveTo(1,4.00,6,1000);
EXEC     Activity#53,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#54,     PANCAM_ACQ(0,5,0);
EXEC     Activity#55,     MAST_PTU_MoveTo(1,8.00,6,1000);
EXEC     Activity#56,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#57,     PANCAM_ACQ(0,5,0);
EXEC     Activity#58,     MAST_PTU_MoveTo(1,12.00,6,1000);
EXEC     Activity#59,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#60,     PANCAM_ACQ(0,5,0);
EXEC     Activity#61,     MAST_PTU_MoveTo(1,16.00,6,1000);
EXEC     Activity#62,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#63,     PANCAM_ACQ(0,5,0);
EXEC     Activity#64,     MAST_PTU_MoveTo(1,20.00,6,1000);
EXEC     Activity#65,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#66,     PANCAM_ACQ(0,5,0);

EXEC     Activity#67,     MAST_PTU_MoveTo(1,-20.00,12,1000);
EXEC     Activity#68,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#69,     PANCAM_ACQ(0,5,0);
EXEC     Activity#70,     MAST_PTU_MoveTo(1,-16.00,12,1000);
EXEC     Activity#71,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#72,     PANCAM_ACQ(0,5,0);
EXEC     Activity#73,     MAST_PTU_MoveTo(1,-12.00,12,1000);
EXEC     Activity#74,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#75,     PANCAM_ACQ(0,5,0);
EXEC     Activity#76,     MAST_PTU_MoveTo(1,-8.00,12,1000);
EXEC     Activity#77,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#78,     PANCAM_ACQ(0,5,0);
EXEC     Activity#79,     MAST_PTU_MoveTo(1,-4.00,12,1000);
EXEC     Activity#80,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#81,     PANCAM_ACQ(0,5,0);
```

```
EXEC     Activity#82,     MAST_PTU_MoveTo(1,0.00,12,1000);
EXEC     Activity#83,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#84,     PANCAM_ACQ(0,5,0);
EXEC     Activity#85,     MAST_PTU_MoveTo(1,4.00,12,1000);
EXEC     Activity#86,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#87,     PANCAM_ACQ(0,5,0);
EXEC     Activity#88,     MAST_PTU_MoveTo(1,8.00,12,1000);
EXEC     Activity#89,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#90,     PANCAM_ACQ(0,5,0);
EXEC     Activity#91,     MAST_PTU_MoveTo(1,12.00,12,1000);
EXEC     Activity#92,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#93,     PANCAM_ACQ(0,5,0);
EXEC     Activity#94,     MAST_PTU_MoveTo(1,16.00,12,1000);
EXEC     Activity#95,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#96,     PANCAM_ACQ(0,5,0);
EXEC     Activity#97,     MAST_PTU_MoveTo(1,20.00,12,1000);
EXEC     Activity#98,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#99,     PANCAM_ACQ(0,5,0);

EXEC     Activity#100,    MAST_PTU_MoveTo(1,-20.00,18,1000);
EXEC     Activity#101,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#102,    PANCAM_ACQ(0,5,0);
EXEC     Activity#103,    MAST_PTU_MoveTo(1,-16.00,18,1000);
EXEC     Activity#104,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#105,    PANCAM_ACQ(0,5,0);
EXEC     Activity#106,    MAST_PTU_MoveTo(1,-12.00,18,1000);
EXEC     Activity#107,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#108,    PANCAM_ACQ(0,5,0);
EXEC     Activity#109,    MAST_PTU_MoveTo(1,-8.00,18,1000);
EXEC     Activity#110,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#111,    PANCAM_ACQ(0,5,0);
EXEC     Activity#112,    MAST_PTU_MoveTo(1,-4.00,18,1000);
EXEC     Activity#113,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#114,    PANCAM_ACQ(0,5,0);
EXEC     Activity#115,    MAST_PTU_MoveTo(1,0.00,18,1000);
EXEC     Activity#116,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#117,    PANCAM_ACQ(0,5,0);
EXEC     Activity#118,    MAST_PTU_MoveTo(1,4.00,18,1000);
EXEC     Activity#119,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#120,    PANCAM_ACQ(0,5,0);
EXEC     Activity#121,    MAST_PTU_MoveTo(1,8.00,18,1000);
EXEC     Activity#122,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#123,    PANCAM_ACQ(0,5,0);
EXEC     Activity#124,    MAST_PTU_MoveTo(1,12.00,18,1000);
EXEC     Activity#125,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#126,    PANCAM_ACQ(0,5,0);
EXEC     Activity#127,    MAST_PTU_MoveTo(1,16.00,18,1000);
EXEC     Activity#128,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#129,    PANCAM_ACQ(0,5,0);
```

```
EXEC     Activity#130,    MAST_PTU_MoveTo(1,20.00,18,1000);
EXEC     Activity#131,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#132,    PANCAM_ACQ(0,5,0);

EXEC     Activity#133,    MAST_PTU_MoveTo(1,-20.00,24,1000);
EXEC     Activity#134,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#135,    PANCAM_ACQ(0,5,0);
EXEC     Activity#136,    MAST_PTU_MoveTo(1,-16.00,24,1000);
EXEC     Activity#137,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#138,    PANCAM_ACQ(0,5,0);
EXEC     Activity#139,    MAST_PTU_MoveTo(1,-12.00,24,1000);
EXEC     Activity#140,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#141,    PANCAM_ACQ(0,5,0);
EXEC     Activity#142,    MAST_PTU_MoveTo(1,-8.00,24,1000);
EXEC     Activity#143,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#144,    PANCAM_ACQ(0,5,0);
EXEC     Activity#145,    MAST_PTU_MoveTo(1,-4.00,24,1000);
EXEC     Activity#146,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#147,    PANCAM_ACQ(0,5,0);
EXEC     Activity#148,    MAST_PTU_MoveTo(1,0.00,24,1000);
EXEC     Activity#149,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#150,    PANCAM_ACQ(0,5,0);
EXEC     Activity#151,    MAST_PTU_MoveTo(1,4.00,24,1000);
EXEC     Activity#152,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#153,    PANCAM_ACQ(0,5,0);
EXEC     Activity#154,    MAST_PTU_MoveTo(1,8.00,24,1000);
EXEC     Activity#155,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#156,    PANCAM_ACQ(0,5,0);
EXEC     Activity#157,    MAST_PTU_MoveTo(1,12.00,24,1000);
EXEC     Activity#158,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#159,    PANCAM_ACQ(0,5,0);
EXEC     Activity#160,    MAST_PTU_MoveTo(1,16.00,24,1000);
EXEC     Activity#161,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#162,    PANCAM_ACQ(0,5,0);
EXEC     Activity#163,    MAST_PTU_MoveTo(1,20.00,24,1000);
EXEC     Activity#164,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#165,    PANCAM_ACQ(0,5,0);

END_SOL;
```

Activity Plan B.4: WISDOM test 1: camera intrinsic parameters calibration. Poition A.

Test 1: calibration of intrinsic camera parameters.

Position B.

```
EXEC     Activity#1,      MAST_PTU_MoveTo(1,-20.00,-6,1000);
EXEC     Activity#2,      NAVCAM_ACQ(0,5,0);
```

```
EXEC     Activity#3,      PANCAM_ACQ(0,5,0);
EXEC     Activity#4,      MAST_PTU_MoveTo(1,-16.00,-6,1000);
EXEC     Activity#5,      NAVCAM_ACQ(0,5,0);
EXEC     Activity#6,      PANCAM_ACQ(0,5,0);
EXEC     Activity#7,      MAST_PTU_MoveTo(1,-12.00,-6,1000);
EXEC     Activity#8,      NAVCAM_ACQ(0,5,0);
EXEC     Activity#9,      PANCAM_ACQ(0,5,0);
EXEC     Activity#10,     MAST_PTU_MoveTo(1,-8.00,-6,1000);
EXEC     Activity#11,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#12,     PANCAM_ACQ(0,5,0);
EXEC     Activity#13,     MAST_PTU_MoveTo(1,-4.00,-6,1000);
EXEC     Activity#14,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#15,     PANCAM_ACQ(0,5,0);
EXEC     Activity#16,     MAST_PTU_MoveTo(1,0.00,-6,1000);
EXEC     Activity#17,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#18,     PANCAM_ACQ(0,5,0);
EXEC     Activity#19,     MAST_PTU_MoveTo(1,4.00,-6,1000);
EXEC     Activity#20,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#21,     PANCAM_ACQ(0,5,0);
EXEC     Activity#22,     MAST_PTU_MoveTo(1,8.00,-6,1000);
EXEC     Activity#23,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#24,     PANCAM_ACQ(0,5,0);
EXEC     Activity#25,     MAST_PTU_MoveTo(1,12.00,-6,1000);
EXEC     Activity#26,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#27,     PANCAM_ACQ(0,5,0);
EXEC     Activity#28,     MAST_PTU_MoveTo(1,16.00,-6,1000);
EXEC     Activity#29,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#30,     PANCAM_ACQ(0,5,0);
EXEC     Activity#31,     MAST_PTU_MoveTo(1,20.00,-6,1000);
EXEC     Activity#32,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#33,     PANCAM_ACQ(0,5,0);

EXEC     Activity#34,     MAST_PTU_MoveTo(1,-20.00,0,1000);
EXEC     Activity#35,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#36,     PANCAM_ACQ(0,5,0);
EXEC     Activity#37,     MAST_PTU_MoveTo(1,-16.00,0,1000);
EXEC     Activity#38,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#39,     PANCAM_ACQ(0,5,0);
EXEC     Activity#40,     MAST_PTU_MoveTo(1,-12.00,0,1000);
EXEC     Activity#41,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#42,     PANCAM_ACQ(0,5,0);
EXEC     Activity#43,     MAST_PTU_MoveTo(1,-8.00,0,1000);
EXEC     Activity#44,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#45,     PANCAM_ACQ(0,5,0);
EXEC     Activity#46,     MAST_PTU_MoveTo(1,-4.00,0,1000);
EXEC     Activity#47,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#48,     PANCAM_ACQ(0,5,0);
EXEC     Activity#49,     MAST_PTU_MoveTo(1,0.00,0,1000);
EXEC     Activity#50,     NAVCAM_ACQ(0,5,0);
```

```
EXEC     Activity#51,     PANCAM_ACQ(0,5,0);
EXEC     Activity#52,     MAST_PTU_MoveTo(1,4.00,0,1000);
EXEC     Activity#53,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#54,     PANCAM_ACQ(0,5,0);
EXEC     Activity#55,     MAST_PTU_MoveTo(1,8.00,0,1000);
EXEC     Activity#56,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#57,     PANCAM_ACQ(0,5,0);
EXEC     Activity#58,     MAST_PTU_MoveTo(1,12.00,0,1000);
EXEC     Activity#59,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#60,     PANCAM_ACQ(0,5,0);
EXEC     Activity#61,     MAST_PTU_MoveTo(1,16.00,0,1000);
EXEC     Activity#62,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#63,     PANCAM_ACQ(0,5,0);
EXEC     Activity#64,     MAST_PTU_MoveTo(1,20.00,0,1000);
EXEC     Activity#65,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#66,     PANCAM_ACQ(0,5,0);

EXEC     Activity#67,     MAST_PTU_MoveTo(1,-20.00,6,1000);
EXEC     Activity#68,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#69,     PANCAM_ACQ(0,5,0);
EXEC     Activity#70,     MAST_PTU_MoveTo(1,-16.00,6,1000);
EXEC     Activity#71,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#72,     PANCAM_ACQ(0,5,0);
EXEC     Activity#73,     MAST_PTU_MoveTo(1,-12.00,6,1000);
EXEC     Activity#74,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#75,     PANCAM_ACQ(0,5,0);
EXEC     Activity#76,     MAST_PTU_MoveTo(1,-8.00,6,1000);
EXEC     Activity#77,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#78,     PANCAM_ACQ(0,5,0);
EXEC     Activity#79,     MAST_PTU_MoveTo(1,-4.00,6,1000);
EXEC     Activity#80,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#81,     PANCAM_ACQ(0,5,0);
EXEC     Activity#82,     MAST_PTU_MoveTo(1,0.00,6,1000);
EXEC     Activity#83,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#84,     PANCAM_ACQ(0,5,0);
EXEC     Activity#85,     MAST_PTU_MoveTo(1,4.00,6,1000);
EXEC     Activity#86,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#87,     PANCAM_ACQ(0,5,0);
EXEC     Activity#88,     MAST_PTU_MoveTo(1,8.00,6,1000);
EXEC     Activity#89,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#90,     PANCAM_ACQ(0,5,0);
EXEC     Activity#91,     MAST_PTU_MoveTo(1,12.00,6,1000);
EXEC     Activity#92,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#93,     PANCAM_ACQ(0,5,0);
EXEC     Activity#94,     MAST_PTU_MoveTo(1,16.00,6,1000);
EXEC     Activity#95,     NAVCAM_ACQ(0,5,0);
EXEC     Activity#96,     PANCAM_ACQ(0,5,0);
EXEC     Activity#97,     MAST_PTU_MoveTo(1,20.00,6,1000);
EXEC     Activity#98,     NAVCAM_ACQ(0,5,0);
```

```
EXEC     Activity#99,     PANCAM_ACQ(0,5,0);

EXEC     Activity#100,    MAST_PTU_MoveTo(1,-20.00,12,1000);
EXEC     Activity#101,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#102,    PANCAM_ACQ(0,5,0);
EXEC     Activity#103,    MAST_PTU_MoveTo(1,-16.00,12,1000);
EXEC     Activity#104,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#105,    PANCAM_ACQ(0,5,0);
EXEC     Activity#106,    MAST_PTU_MoveTo(1,-12.00,12,1000);
EXEC     Activity#107,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#108,    PANCAM_ACQ(0,5,0);
EXEC     Activity#109,    MAST_PTU_MoveTo(1,-8.00,12,1000);
EXEC     Activity#110,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#111,    PANCAM_ACQ(0,5,0);
EXEC     Activity#112,    MAST_PTU_MoveTo(1,-4.00,12,1000);
EXEC     Activity#113,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#114,    PANCAM_ACQ(0,5,0);
EXEC     Activity#115,    MAST_PTU_MoveTo(1,0.00,12,1000);
EXEC     Activity#116,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#117,    PANCAM_ACQ(0,5,0);
EXEC     Activity#118,    MAST_PTU_MoveTo(1,4.00,12,1000);
EXEC     Activity#119,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#120,    PANCAM_ACQ(0,5,0);
EXEC     Activity#121,    MAST_PTU_MoveTo(1,8.00,12,1000);
EXEC     Activity#122,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#123,    PANCAM_ACQ(0,5,0);
EXEC     Activity#124,    MAST_PTU_MoveTo(1,12.00,12,1000);
EXEC     Activity#125,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#126,    PANCAM_ACQ(0,5,0);
EXEC     Activity#127,    MAST_PTU_MoveTo(1,16.00,12,1000);
EXEC     Activity#128,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#129,    PANCAM_ACQ(0,5,0);
EXEC     Activity#130,    MAST_PTU_MoveTo(1,20.00,12,1000);
EXEC     Activity#131,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#132,    PANCAM_ACQ(0,5,0);

EXEC     Activity#133,    MAST_PTU_MoveTo(1,-20.00,18,1000);
EXEC     Activity#134,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#135,    PANCAM_ACQ(0,5,0);
EXEC     Activity#136,    MAST_PTU_MoveTo(1,-16.00,18,1000);
EXEC     Activity#137,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#138,    PANCAM_ACQ(0,5,0);
EXEC     Activity#139,    MAST_PTU_MoveTo(1,-12.00,18,1000);
EXEC     Activity#140,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#141,    PANCAM_ACQ(0,5,0);
EXEC     Activity#142,    MAST_PTU_MoveTo(1,-8.00,18,1000);
EXEC     Activity#143,    NAVCAM_ACQ(0,5,0);
EXEC     Activity#144,    PANCAM_ACQ(0,5,0);
EXEC     Activity#145,    MAST_PTU_MoveTo(1,-4.00,18,1000);
```

```
EXEC     Activity#146,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#147,   PANCAM_ACQ(0,5,0);
EXEC     Activity#148,   MAST_PTU_MoveTo(1,0.00,18,1000);
EXEC     Activity#149,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#150,   PANCAM_ACQ(0,5,0);
EXEC     Activity#151,   MAST_PTU_MoveTo(1,4.00,18,1000);
EXEC     Activity#152,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#153,   PANCAM_ACQ(0,5,0);
EXEC     Activity#154,   MAST_PTU_MoveTo(1,8.00,18,1000);
EXEC     Activity#155,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#156,   PANCAM_ACQ(0,5,0);
EXEC     Activity#157,   MAST_PTU_MoveTo(1,12.00,18,1000);
EXEC     Activity#158,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#159,   PANCAM_ACQ(0,5,0);
EXEC     Activity#160,   MAST_PTU_MoveTo(1,16.00,18,1000);
EXEC     Activity#161,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#162,   PANCAM_ACQ(0,5,0);
EXEC     Activity#163,   MAST_PTU_MoveTo(1,20.00,18,1000);
EXEC     Activity#164,   NAVCAM_ACQ(0,5,0);
EXEC     Activity#165,   PANCAM_ACQ(0,5,0);

END_SOL;
```

Activity Plan B.5: WISDOM test 1: camera intrinsic parameters calibration. Poition B.

Test 2: calibration of extrinsic camera parameters.

```
EXEC     A0,      MAST_PTU_MoveTo(1,0,20,100);
EXEC     A1,      NAVCAM_ACQ(0,5,0);
EXEC     A2,      PANCAM_ACQ(0,5,0);

END_SOL;
```

Activity Plan B.6: WISDOM test 2: camera extrinsic parameters calibration.

Test 3: WISDOM grid execution.

```
# PANORAMA
EXEC     A49,     GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A98,     GNC_TURNSPOT_GOTO(1,-30,0.5,1000);
EXEC     A99,     GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A148,    GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A197,    GNC_TURNSPOT_GOTO(1,-30,0.5,1000);
```

```
EXEC    A198,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A247,   GNC_TURNSPOT_GOTO(1,-30,0.5,1000);
EXEC    A248,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A297,   GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC    A298,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A347,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A396,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A445,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A494,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A543,   GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC    A544,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A593,   GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC    A594,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A643,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A692,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A741,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A790,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A839,   GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC    A840,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A889,   GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC    A890,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A939,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A988,   GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A1037,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A1086,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A1135,  GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC    A1136,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC    A1185,  GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC    A1186,  GNC_LLO(1,1,0.02);
```

```
# PANORAMA
EXEC     A1235,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1284,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1333,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1382,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1431,  GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC     A1432,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1481,  GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC     A1482,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1531,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1580,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1629,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1678,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1727,  GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC     A1728,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1777,  GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC     A1778,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1827,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1876,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1925,  GNC_LLO(1,1,0.02);
# PANORAMA
EXEC     A1974,  GNC_LLO(1,1,0.02);
# PANORAMA

END_SOL;
```

Activity Plan B.7: WISDOM test 3: WISDOM grid execution.

In the latter AP each comment `# PANORAMA` re-call a *panorama acquisition AP* similar to:

```
EXEC     A1,     MAST_PTU_MoveTo(1,-235,20,100);
EXEC     A2,     NAVCAM_ACQ(0,5,0);
EXEC     A3,     PANCAM_ACQ(0,5,0);
EXEC     A4,     MAST_PTU_MoveTo(1,-190,20,100);
EXEC     A5,     NAVCAM_ACQ(0,5,0);
EXEC     A6,     PANCAM_ACQ(0,5,0);
```

```
EXEC    A7,     MAST_PTU_MoveTo(1,-145,20,100);
EXEC    A8,     NAVCAM_ACQ(0,5,0);
EXEC    A9,     PANCAM_ACQ(0,5,0);
EXEC    A10,    MAST_PTU_MoveTo(1,-100,20,100);
EXEC    A11,    NAVCAM_ACQ(0,5,0);
EXEC    A12,    PANCAM_ACQ(0,5,0);
EXEC    A13,    MAST_PTU_MoveTo(1,-55,20,100);
EXEC    A14,    NAVCAM_ACQ(0,5,0);
EXEC    A15,    PANCAM_ACQ(0,5,0);
EXEC    A16,    MAST_PTU_MoveTo(1,-10,20,100);
EXEC    A17,    NAVCAM_ACQ(0,5,0);
EXEC    A18,    PANCAM_ACQ(0,5,0);
EXEC    A19,    MAST_PTU_MoveTo(1,35,20,100);
EXEC    A20,    NAVCAM_ACQ(0,5,0);
EXEC    A21,    PANCAM_ACQ(0,5,0);
EXEC    A22,    MAST_PTU_MoveTo(1,50,20,100);
EXEC    A23,    NAVCAM_ACQ(0,5,0);
EXEC    A24,    PANCAM_ACQ(0,5,0);
EXEC    A25,    MAST_PTU_MoveTo(1,-235,30,100);
EXEC    A26,    NAVCAM_ACQ(0,5,0);
EXEC    A27,    PANCAM_ACQ(0,5,0);
EXEC    A28,    MAST_PTU_MoveTo(1,-190,30,100);
EXEC    A29,    NAVCAM_ACQ(0,5,0);
EXEC    A30,    PANCAM_ACQ(0,5,0);
EXEC    A31,    MAST_PTU_MoveTo(1,-145,30,100);
EXEC    A32,    NAVCAM_ACQ(0,5,0);
EXEC    A33,    PANCAM_ACQ(0,5,0);
EXEC    A34,    MAST_PTU_MoveTo(1,-100,30,100);
EXEC    A35,    NAVCAM_ACQ(0,5,0);
EXEC    A36,    PANCAM_ACQ(0,5,0);
EXEC    A37,    MAST_PTU_MoveTo(1,-55,30,100);
EXEC    A38,    NAVCAM_ACQ(0,5,0);
EXEC    A39,    PANCAM_ACQ(0,5,0);
EXEC    A40,    MAST_PTU_MoveTo(1,-10,30,100);
EXEC    A41,    NAVCAM_ACQ(0,5,0);
EXEC    A42,    PANCAM_ACQ(0,5,0);
EXEC    A43,    MAST_PTU_MoveTo(1,35,30,100);
EXEC    A44,    NAVCAM_ACQ(0,5,0);
EXEC    A45,    PANCAM_ACQ(0,5,0);
EXEC    A46,    MAST_PTU_MoveTo(1,50,30,100);
EXEC    A47,    NAVCAM_ACQ(0,5,0);
EXEC    A48,    PANCAM_ACQ(0,5,0);
```

Activity Plan B.8: Panorama acquisition.

Test 4: sunset scenario.

```
EXEC    A0,     MAST_PTU_MoveTo(1,-235,20,100);
```

```
EXEC    A1,     NAVCAM_ACQ(0,5,0);
EXEC    A2,     PANCAM_ACQ(0,5,0);
EXEC    A3,     MAST_PTU_MoveTo(1,-190,20,100);
EXEC    A4,     NAVCAM_ACQ(0,5,0);
EXEC    A5,     PANCAM_ACQ(0,5,0);
EXEC    A6,     MAST_PTU_MoveTo(1,-145,20,100);
EXEC    A7,     NAVCAM_ACQ(0,5,0);
EXEC    A8,     PANCAM_ACQ(0,5,0);
EXEC    A9,     MAST_PTU_MoveTo(1,-100,20,100);
EXEC    A10,    NAVCAM_ACQ(0,5,0);
EXEC    A11,    PANCAM_ACQ(0,5,0);
EXEC    A12,    MAST_PTU_MoveTo(1,-55,20,100);
EXEC    A13,    NAVCAM_ACQ(0,5,0);
EXEC    A14,    PANCAM_ACQ(0,5,0);
EXEC    A15,    MAST_PTU_MoveTo(1,-10,20,100);
EXEC    A16,    NAVCAM_ACQ(0,5,0);
EXEC    A17,    PANCAM_ACQ(0,5,0);
EXEC    A18,    MAST_PTU_MoveTo(1,35,20,100);
EXEC    A19,    NAVCAM_ACQ(0,5,0);
EXEC    A20,    PANCAM_ACQ(0,5,0);
EXEC    A21,    MAST_PTU_MoveTo(1,50,20,100);
EXEC    A22,    NAVCAM_ACQ(0,5,0);
EXEC    A23,    PANCAM_ACQ(0,5,0);
EXEC    A24,    MAST_PTU_MoveTo(1,-235,10,100);
EXEC    A25,    NAVCAM_ACQ(0,5,0);
EXEC    A26,    PANCAM_ACQ(0,5,0);
EXEC    A27,    MAST_PTU_MoveTo(1,-190,10,100);
EXEC    A28,    NAVCAM_ACQ(0,5,0);
EXEC    A29,    PANCAM_ACQ(0,5,0);
EXEC    A30,    MAST_PTU_MoveTo(1,-145,10,100);
EXEC    A31,    NAVCAM_ACQ(0,5,0);
EXEC    A32,    PANCAM_ACQ(0,5,0);
EXEC    A33,    MAST_PTU_MoveTo(1,-100,10,100);
EXEC    A34,    NAVCAM_ACQ(0,5,0);
EXEC    A35,    PANCAM_ACQ(0,5,0);
EXEC    A36,    MAST_PTU_MoveTo(1,-55,10,100);
EXEC    A37,    NAVCAM_ACQ(0,5,0);
EXEC    A38,    PANCAM_ACQ(0,5,0);
EXEC    A39,    MAST_PTU_MoveTo(1,-10,10,100);
EXEC    A40,    NAVCAM_ACQ(0,5,0);
EXEC    A41,    PANCAM_ACQ(0,5,0);
EXEC    A42,    MAST_PTU_MoveTo(1,35,10,100);
EXEC    A43,    NAVCAM_ACQ(0,5,0);
EXEC    A44,    PANCAM_ACQ(0,5,0);
EXEC    A45,    MAST_PTU_MoveTo(1,50,10,100);
EXEC    A46,    NAVCAM_ACQ(0,5,0);
EXEC    A47,    PANCAM_ACQ(0,5,0);

END_SOL;
```

Activity Plan B.9: WISDOM test 4: sunset condition.

Test 5: WISDOM grid in a single AP.

```
EXEC A1,        MAST_PTU_MoveTo(1,-235,20,100);
EXEC A2,        NAVCAM_ACQ(0,5,0);
EXEC A3,        MAST_PTU_MoveTo(1,-175,20,100);
EXEC A4,        NAVCAM_ACQ(0,5,0);
EXEC A5,        MAST_PTU_MoveTo(1,-115,20,100);
EXEC A6,        NAVCAM_ACQ(0,5,0);
EXEC A7,        MAST_PTU_MoveTo(1,-55,20,100);
EXEC A8,        NAVCAM_ACQ(0,5,0);
EXEC A9,        MAST_PTU_MoveTo(1,5,20,100);
EXEC A10,       NAVCAM_ACQ(0,5,0);
EXEC A11,       GNC_LLO (1,1,0.02 );
EXEC A12,       GNC_TURNSPOT_GOTO(1,-30,0.5,1000);
EXEC A13,       GNC_LLO (1,2,0.02);
EXEC A14,       GNC_TURNSPOT_GOTO(1,-30,0.5,1000);
EXEC A15,       GNC_LLO (1,1,0.02);
EXEC A16,       GNC_TURNSPOT_GOTO(1,-30,0.5,1000);
EXEC A17,       GNC_LLO (1,1,0.02);
EXEC A18,       GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC A19,       MAST_PTU_MoveTo(1,-235,20,100);
EXEC A20,       NAVCAM_ACQ(0,5,0);
EXEC A21,       MAST_PTU_MoveTo(1,-175,20,100);
EXEC A22,       NAVCAM_ACQ(0,5,0);
EXEC A23,       MAST_PTU_MoveTo(1,-115,20,100);
EXEC A24,       NAVCAM_ACQ(0,5,0);
EXEC A25,       MAST_PTU_MoveTo(1,-55,20,100);
EXEC A26,       NAVCAM_ACQ(0,5,0);
EXEC A27,       MAST_PTU_MoveTo(1,5,20,100);
EXEC A28,       NAVCAM_ACQ(0,5,0);
EXEC A29,       GNC_LLO (1,5,0.02);
EXEC A30,       MAST_PTU_MoveTo(1,-235,20,100);
EXEC A31,       NAVCAM_ACQ(0,5,0);
EXEC A32,       MAST_PTU_MoveTo(1,-175,20,100);
EXEC A33,       NAVCAM_ACQ(0,5,0);
EXEC A34,       MAST_PTU_MoveTo(1,-115,20,100);
EXEC A35,       NAVCAM_ACQ(0,5,0);
EXEC A36,       MAST_PTU_MoveTo(1,-55,20,100);
EXEC A37,       NAVCAM_ACQ(0,5,0);
EXEC A38,       MAST_PTU_MoveTo(1,5,20,100);
EXEC A39,       NAVCAM_ACQ(0,5,0);
EXEC A40,       GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC A41,       GNC_LLO (1,1,0.02);
EXEC A42,       GNC_TURNSPOT_GOTO(1,90,0.5,1000);
```

```
EXEC A43,        GNC_LLO (1,5,0.02);
EXEC A44,        GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC A45,        GNC_LLO (1,1,0.02);
EXEC A46,        GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC A47,        GNC_LLO (1,5,0.02);
EXEC A48,        GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC A49,        GNC_LLO (1,1,0.02);
EXEC A50,        GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC A51,        GNC_LLO (1,5,0.02);
EXEC A52,        GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC A53,        GNC_LLO (1,1,0.02);
EXEC A54,        GNC_TURNSPOT_GOTO(1,-90,0.5,1000);
EXEC A55,        GNC_LLO (1,5,0.02);
EXEC A56,        GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC A57,        GNC_LLO (1,1,0.02);
EXEC A58,        GNC_TURNSPOT_GOTO(1,90,0.5,1000);
EXEC A59,        MAST_PTU_MoveTo(1,-235,20,100);
EXEC A60,        NAVCAM_ACQ(0,5,0);
EXEC A61,        MAST_PTU_MoveTo(1,-175,20,100);
EXEC A62,        NAVCAM_ACQ(0,5,0);
EXEC A63,        MAST_PTU_MoveTo(1,-115,20,100);
EXEC A64,        NAVCAM_ACQ(0,5,0);
EXEC A65,        MAST_PTU_MoveTo(1,-55,20,100);
EXEC A66,        NAVCAM_ACQ(0,5,0);
EXEC A67,        MAST_PTU_MoveTo(1,5,20,100);
EXEC A68,        NAVCAM_ACQ(0,5,0);
EXEC A69,        GNC_LLO (1,5,0.02);
EXEC A70,        MAST_PTU_MoveTo(1,-235,20,100);
EXEC A71,        NAVCAM_ACQ(0,5,0);
EXEC A72,        MAST_PTU_MoveTo(1,-175,20,100);
EXEC A73,        NAVCAM_ACQ(0,5,0);
EXEC A74,        MAST_PTU_MoveTo(1,-115,20,100);
EXEC A75,        NAVCAM_ACQ(0,5,0);
EXEC A76,        MAST_PTU_MoveTo(1,-55,20,100);
EXEC A77,        NAVCAM_ACQ(0,5,0);
EXEC A78,        MAST_PTU_MoveTo(1,5,20,100);
EXEC A79,        NAVCAM_ACQ(0,5,0);

END_SOL;
```

Activity Plan B.10: WISDOM test 5: WISDOM grid (single AP).

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