REMOTE ROVER OPERATIONS: TESTING THE EXOMARS EGRESS CASE

Martin Azkarate[1], Konstantinos Kapellos[2], Rob Hewitt[1], Evangelos Boukas[1], Luc Joudrier[1], Pantelis Poulakis[1], Alex Torres[3], Diego Bussi[4], Enrico Ferrentino[4], and Gianfranco Visentin[1]

[1]*European Space Agency, ESA, Noordwijk, The Netherlands*
[2]*TRASYS, Terhulpsesteenweg 6C -1560 Hoeilaart, Belgium*
[3]*CNES, 18 Avenue Edouard Belin, Toulouse, France*
[4]*ALTEC, Turin, Italy*

ABSTRACT

This paper presents the results of the remote rover operations tests run on the 27-29th of October 2015 focused on the ExoMars egress manoeuvre scenario. A total of 5 differently challenging scenarios were tested in order to evaluate the capabilities of the operators with regards to the proper understanding of the criticality of each case that would allow them to make a sound decision on which egress direction to take. These experiments showed the usability of simulation tools 3DROCS & 3DROV for acquiring the situational awareness needed for this purpose and the importance of planning and establishing the rules and conditions that enable the decision making process.

Key words: ExoMars, Rover operations, Egress, ROCC SW Tools.

1. INTRODUCTION

Approaching the ExoMars 2018 Rover Mission launch date, the Robotics section of ESA/ESTEC has decided to restart the effort on remote rover operations activities, which are crucial for the successful execution of the mission and so far have proved very important to understand some not-apparent im/com-plications of remotely operating a rover. Particularly, the Egress manoeuvre was deemed not only interesting but also urgently relevant to be tested, in order to gain some hands-on experience in the operation of such a critical initial mission phase. Rover operation of planetary rovers entails several systems connected into a communication chain:

Rover ⇔ Data Relay Satellite (DRS) ⇔ Space Network ⇔ Mission Operation Centre (MOC) ⇔ Rover Operation Control Centre (ROCC)

ESTEC has already performed tests in the last years considering the end-to-end system, i.e., from/to Rover to/from ROCC [1] [2]. These activities have allowed to build up some confidence on the suitability of operation interfaces, and rover sensoring that provide enough situational awareness to operate the rover. Additionally, in ESOC there has been prototyping to address covering the interoperability between mission operations and rover operations systems [3]. This has provided valuable inputs to related standardization activities and has allowed for validation of proposed related concepts and technologies. Regrettably so far the full end-to-end scenario has not been addressed for planetary science robotic missions, for which real constraints of a space mission need to be taken into account.

2. TEST OBJECTIVES

The tests presented in this paper aimed to take a step further in the realisation of a more representative operation scenario by using the latest developed tools for rover mission planning and execution 3DROCS [5], together with the already established rover dynamics simulation tool 3DROV [4]. As already mentioned, the focus of these tests was put on the Egress manoeuvre, and furthermore, it was highly relevant to assess whether the SW tools and telemetry data available at the current configuration of the rover were adequate and sufficient for the ROCC to operate the rover. Therefore the objective was the development of experimental knowledge and to explore the limitations, constraints but also opportunities that the whole end-to-end chain impart/allows. The test also aimed to increase the collaboration between the participating agencies and industrial partners. While the rover was placed in the CNES Mars simulate terrain (SEROM), the ROCC was set up in ESTEC and the MOC was arranged in ESOC. On top of that, industrial partners from the ExoMars mission also participated including key members of TRASYS, TAS-I and ALTEC.

3. TEST PREPARATION AND SETUP

Significant effort was put in the shaping of the test and many ideas were considered until the objectives and final setup was reached. Most of the considered ideas in this process can be found in [6] and the result of it is summarised in the schematic in Figure 1.

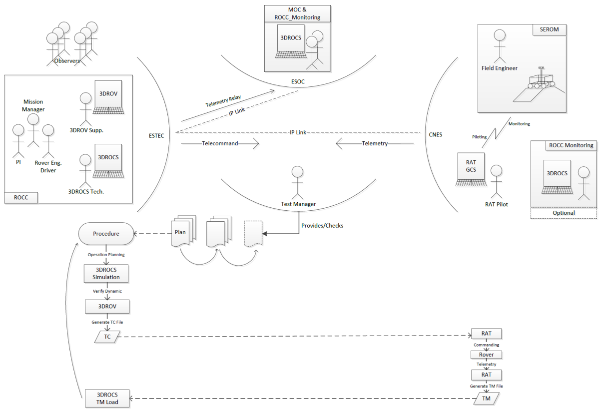

Figure 1. Test setup schematic overview

As the schematic shows, the field test team with the rover was located in SEROM at CNES. The setup included the ExoMars-like laboratory rover prototype, i.e ExoTeR, and Lander system and Local Ground Control Station. The optional 3DROCS station was discarded finally. ESTEC was the base for the ROCC setup with both 3DROV and 3DROCS software stations. Key roles in the ROCC were performed by ExoMars Team members (ESA and industry). The test manager was also set in ESTEC but separate to the ROCC and had a continuous voice link to the Field Test Team in CNES. This proved to be quite useful, if not necessary, for the successful execution of the tests. The setup in ESOC included a monitoring 3DROCS station. The telemetry data received from the rover was relayed to ESOC as well and the field test execution could be followed this way.

Prior to the actual campaign a set of 12 egress scenarios were prepared, each of them willing to exercise a different aspect or risk of an egress, such as slopes, ramps inclinations or presence of rocks. An example of a prepared test case is shown in Figure 2.

The full set of prepared scenarios was only visible to the members that were not participating in the ROCC at ESTEC and only the crew in CNES and the Test Manager knew which scenario was being tested at the time of test execution.

3.1. Rover stability and decision process steps

The rover system needed to be characterised in terms of (static) stability and step height clearance at the end of a ramp. The rover and lander system were actually tested

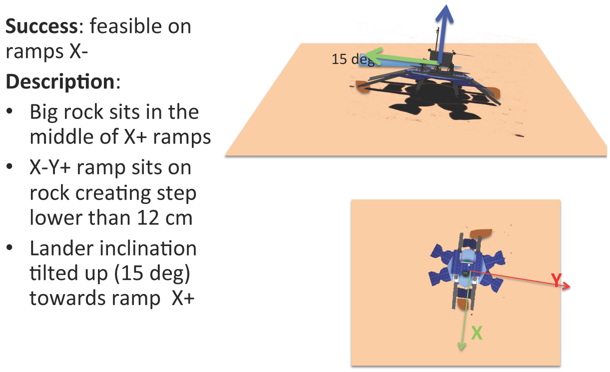

Figure 2. Example of prepared egress scenario

together by inclining the lander platform to the point the rover was starting to tilt over. We found the rover stability to be roughly around 40 degrees in the primary directions while the combination of pitch and roll inclinations reduced the stability to 30 degrees. Analytically the rover stability can also be calculated according to its kinematic properties. The objective is finally to provide the rover operations group a stability envelope that can be used to asses the risk of capsizing over a certain egress direction. The stability envelope calculated for ExoTeR rover can be found in Figure 3.

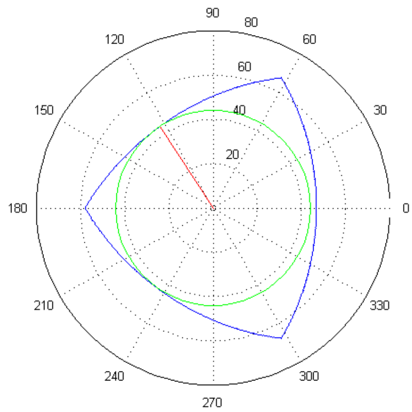

Figure 3. Stability envelope (blue), direction of minimum stability (red) and conservative authorized envelope (green) for ExoTeR

On the other hand, the step clearance was scaled from the ExoMars datasheets and was assumed to be of approximately $12cm$ on horizontal plane and was reducing gradually with the inclination of the ramps. This data was used in combination with a check list containing a series of estimated values to be extracted from the TM data. This way, the decision making process could be organised and focused to the point and each person could be dedicated to accomplish an specific task in this process. An example of the values to be estimated in the decision making process is shown in Figure 4.

Rover & plateform attitude PITCH		0.6	deg	< 20 deg ?		
Rover & plateform attitude ROLL		1.1	deg	< 20 deg ?		
Mast Deployed?		1				
Solar Array Deployed?		1				
	Ramp FL inclination vs platform?		deg	Ramp RL inclination ?		deg
	Ramp FR inclination vs platform?		deg	Ramp RR inclination ?		deg
	Ramp FL inclination vs horizon?		deg	Ramp RL inclination ?		deg
	Ramp FR inclination vs horizon?		deg	Ramp RR inclination ?		deg
	Step FL ?		cm	Step RL ?	0	cm
	Step FR ?		cm	Step RR ?	0	cm
Egress stability clear?			**Egress stability clear?**			
Path F clear ?		0	**Path R clear ?**		1	
Dynamic F success?			**Dynamic R success?**			
Comment	The forward path is not clear from rocks assessed above rover capabilities. Forward path not considered					
DECISION	EGRESS FORWARD		EGRESS REAR			

Figure 4. Decision making progress check list

At the same time, in order to reach the point of deciding on an egress path a set of telemetry and telecommand (TM/TC) messages needed to be sent between the Rover system in SEROM and the ROCC in ESTEC. In order to respect the conditions of the communication chain of a real mission scenario, the communication was limited in bandwidth and availability and could only be used at certain pre-stablished times. A nominal pre-stablished timeline of TM/TC packages was prepared which would exemplify the ideal case where no major risks are found after landing. This timeline was a priori validated by ESOC, to make sure it complied with the ExoMars mission phase.

4. OPERATIONS SUPPORT SW TOOLS

In this section the main characteristics and features of the SW Tools used at the ROCC for rover planning, TM displaying and simulating are explained:

4.1. 3DROCS rover activity planning and scheduling simulation tool

The 3DROCS tool has been developed with the main objective to reduce the tactical planning process time, to increase the user awareness on the system behaviour, to improve the Activity Plan understanding and to provide a unified interface for strategic and tactical planning. To this end, 3DROCS exploits as much as possible the spatiotemporal nature of the rover operations since the location on the planet and the time an operation is executed shall be jointly considered during operations specification and data analysis. In the case of these experiments (Egress manoeuvre), the main objective of the 3DROCS is to import, visualise and provide the operator the means to analyse the rover TM in order to:

- Visualise in the 3D scene ExoTer and the lander.
- Import the DEMs generated by the rover.
- Project on the terrain the images acquired.

4.2. 3DROV rover dynamics simulation tool

The objective of the rover dynamic simulation tool in the Egress experiments is to check the capacity of the rover to descend the rails of the lander considering the dynamic characteristics of the rover in combination with the inclination of the lander and of the rails as well as the characteristics of the terrain (e.g. presence of a rock) at the vicinity of the lander. The main building blocks of 3DROV are shown in Figure 5.

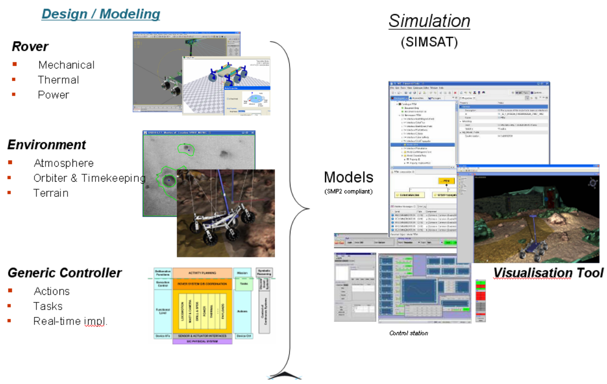

Figure 5. 3DROV building blocks

For the Egress experiments the 3D Visualisation component is mainly used. In particular, the following items are considered:

- The dynamic model of the ExoTer rover: it includes the inertia characteristics of the bodies of the system, the system joints and the friction and restitution characteristics of the wheels.
- The kinematic model of the Lander (considered as a body with collision characteristics) including the rails with the associated joints.
- The environment model consists of the DEM as generated by the ExoTer and imported in the system.

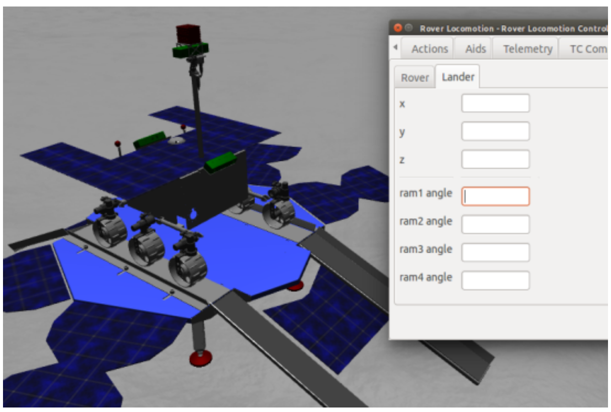

Figure 6. The 3DROV Visualisation tool instantiation for the Egress experiment

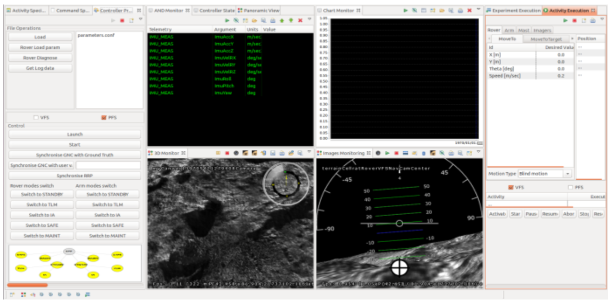

Figure 7. The RAT GCS views

4.3. ExoTeR Local Control Station

The ExoTer Local Control Station is based on the RAT GCS that provides an end-to-end system for specification, validation by simulation, monitoring and control of rover operations. It supports both Interactive Autonomy (IA) and Telemanipulation operational modes (see Figure 7).

During the Egress test this tool is used for the direct commanding of the rover at the field testing site, reducing the used set of components to: *Adiministration*, *Activity Execution*, *Monitoring* and *Communication Server* components.

The objective of the ExoTer Local Control Station in these tests is:

- To control the ExoTer at Interactive Autonomy mode (start/pause/resume on -board Activities),
- To monitor the evolution of the experiments via the TM generated by the ExoTer,
- To log the ExoTer TM to be transferred to the ROCC.

4.4. Test Schedule

A total of 5 different Egress scenarios were run, without counting on preparation tests and dry runs. Tuesday the 27th of October 2015 the equipment was installed in CNES at the SEROM facilities and tested with the ROCC in ESTEC. On Wednesday the 28th the official tests begun and two egress cases were completed. On Thursday the 29th three additional tests were executed. In the following section the outcome of these tests is described and the lessons learnt are given.

5. TEST OUTCOME

In this section the test campaign is evaluated from the point of view of the tools used and setup made. First the execution of one example test scenario is explained by showing exchanged TM/TC data and then stress is put in analysing which aspects of the tests were successful and appropriately set and which were not.

5.1. Samples of TM/TC data

In order to start a test the rover and lander have to be positioned first according to a certain prepared scenario. In Figure 8 the actual setup corresponding the the scenario in Figure 2 is shown.

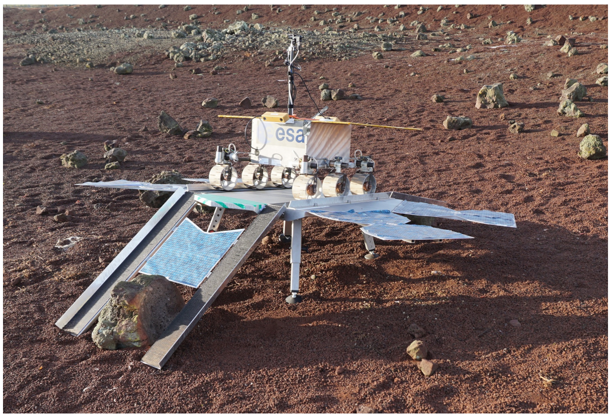

Figure 8. Photo of Example Egress scenario setup in SEROM

Every egress tests starts with the automated activity plan of retrieving rover housekeeping data (including rover stability, i.e, IMU data) and front localisation camera and rear panoramic camera (simulating stowed mast) stereo images. This already allows to set the inclination (orientation) of the lander & rover system and to get from the stereo images the first impression on the scenario (see Figure 9).

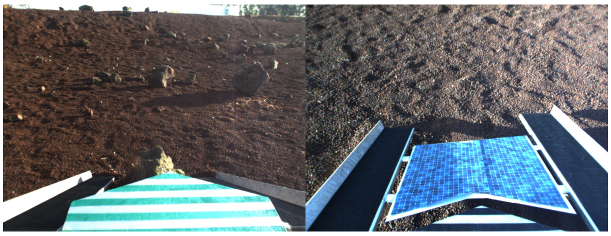

Figure 9. Left: single image of the front localisation stereo camera. Right: single image of the rear panoramic stereo camera (stowed mast).

If the images don't reveal any major issues this is followed by a command to deploy mast and solar array subsystems and to proceed with the acquisition of a full panoramic stereo image and DEM generation. The result of this activity plan (successful or not) is sent back in a TM package in the following communication pass. If the mast is deployed correctly the panoramic images (see Figure 10) allow to get a 360 view of the surrounding area and generating DEMs (see Figure 11) providing the means to estimate obstacle sizes, ramps inclination and any other kind of hazards.

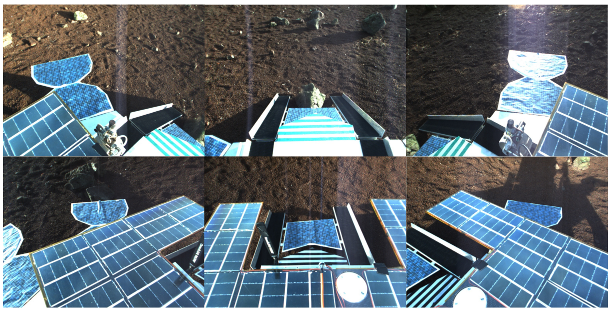

Figure 10. Six single panoramic images taken from the Panoramic stereo camera

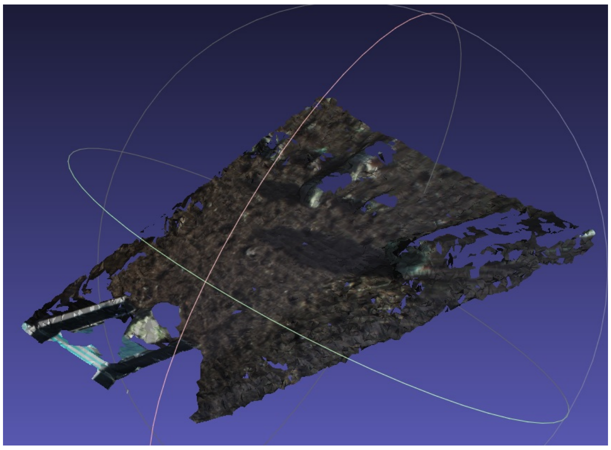

Figure 11. DEM reconstruction from stereo image

All this information is imported to the ROCC SW tools (see Section 4) and evaluated in order to generate the next activity plan. A photo of the ROCC during the execution of a test is shown in Figure 12.

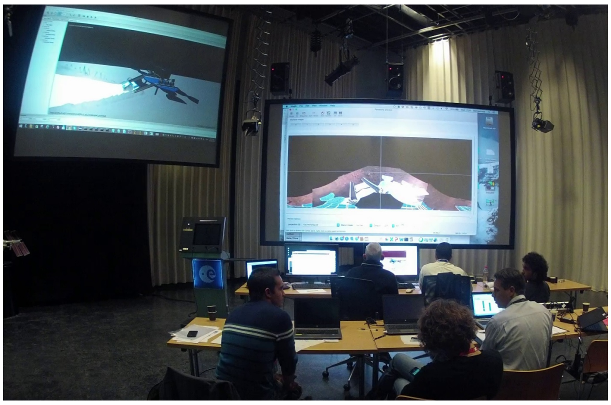

Figure 12. Import of images and DEMs in ROCC. Note stitching of panoramic images and projection of DEMs and images in the 3D visualisation tools

If the provided TM data is enough to estimate the risk of each egress path the rover is commanded to take the safest way out. For this purpose, the values shown in the decision process table in Figure 4 need to be estimated. The result of the operation is checked within the next (and last) TM packet sent. The IMU data and new panoramic images can show the stable rover fully outside of the lander. On top of that we also counted on confirmation from orbital imagery as seen in Figure 13. Four out of the five egress cases succeeded in the egress operation. One of the egress test cases made the rover to capsize due to an error of overestimation of the stability limits of the rover.

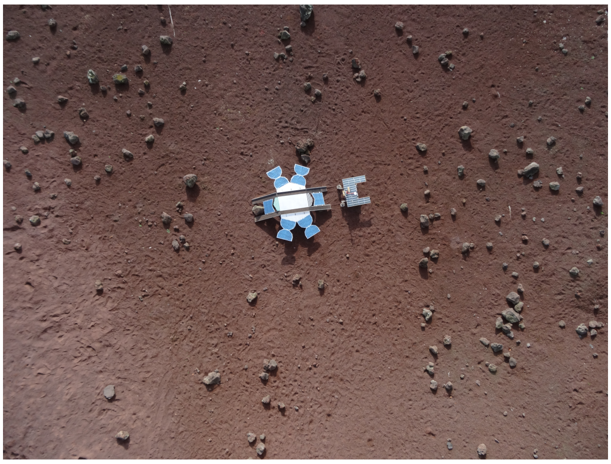

Figure 13. Orbital image confirming egress of the rover

5.2. Regarding the ExoMars Scenario

Participants of the test campaign found the experience very interesting and relevant to future ExoMars-related activities. The systems and interfaces put in place were found appropriate to rehearse on the end-to-end remote operations. Main output of the test was that the instrumentation provided by the system seems adequate to perceive the risks involved in the egress manoeuvre and allow the operators to take an informed and sound decision. This is a very important result and that is why a lot of creativity was put in the test setups, introducing hidden traps to test if operators were able to identify them and estimate the level of risk involved. More precisely, the operators were able to estimate the obstacle sizes, lander inclination, ramps inclination, step down clearance and presence of rocks on the exit routes of the lander. Eventually ExoMars needs to guarantee that the TM data from the rover mission instrumentation is sufficient for the safe execution of the egress manoeuvre. Particularly, the test highlighted that the gravity vector measurement with the rover IMU is the essential notion where all the other relates, especially the rover stability which is one of the first criterion for choosing the egress route.

The landing situations were (on purpose) always very challenging and allowed to progress on the simplified decision steps leading to egress, considering that (in principle) there was always at least one Egress Path within qualified performances. Additionally, should the situation be beyond the nominal case, the partial deployment of the rover mobility system will allow to increase the rover stability (wheel walking case).

During one of the tests the rover capsized mainly due to the limited knowledge of the rover stability in extreme conditions of combined Roll & Pitch, which was affected by the elements that had been mounted on the rover for the test campaign, modifying significantly the initial estimated stability characteristics of the rover. It is clear that for the ExoMars operations, the CoG will be very well known. Limit stability conditions will be also better known and in case of doubt, actual tests with the Ground Test Model would be required at ROCC. Also note that wheel walking actuation was not being used at the test. The good point is that this event showed that it can actually happen. With respect to the decision process, it is important to note that the egress path chosen was the one that the test case was expecting (recommended egress route). The testing of the other path considered much more challenging was also performed and was actually (unexpectedly) successful. The trade-off between overcoming a larger rock or entering the stability limits shall be further explored based on the actual capabilities of the rover. Therefore, Engineering Team at ROCC shall have the necessary knowledge to allow recommending the safest egress path.

While ExoMars Rover mission is expecting to egress within 10 sols after landing, the test were accelerated in order to experiment several egress scenarios. Although several steps have been simplified and skipped in order to allow analysis and decision making process to take place, the decision to skip rover commanding opportunities had to be taken several times, while there was also no urgency to egress. This would be still the case in the real operations but authors are confident that with some automation of on-ground computations, the step by step decisions could be reasonably performed in due time. It is worth mentioning that while the complexity of the real ExoMars rover was very much simplified, the type of commanding via activity plan with high level commands was rather realistic.

On the other hand, the role distribution in the ROCC and MOC was also relevant for the proper execution of the tests. Participants had been named according to the roles implemented and the distribution of tasks allowed everybody to focus and increase the efficiency of the decision making process (see Figure 4) and the work of the Operations Manager.

Finally, it is also clear that such test was performed with inherent inefficiencies that real operations would not have such as:

- Only draft and high level procedures for Egress
- No detailed procedures for the intermediate steps
- No prior training or advanced testing of the tools

5.3. Regarding the interfaces, tools and equipment used

First point to remark is the effort made by everyone for the organisation and collaboration between different agencies and entities. Putting together all the interfaces and joining in a single activity so many people convinced to work together was one of the main achievements. This becomes even more relevant when realising that a big percentage of the test campaign was prepared in the last 6-8 weeks. For future tests, preparation work could be followed with milestones and more formalism. Also dry run showed to be instrumental to the finalisation and consolidation of the system. In terms of interfaces it is worth mentioning the importance of the role played by the Test Manager Team that was found necessary to have a continuous coordination of the test. Actually the pre-stablished timing for the communication windows was just too hard to maintain during the tests. Flexibility in the communication slots became mandatory and the Test Managers were crucial for that. The SW tools used to manage the planning of the rover activities and display of TM data were very useful and absolutely necessary for the execution of the remote operations. Projection of images and DEMs, adjustment of rover orientation and, lander and ramps inclinations and eventually all details that would help recreate in the simulated environment of the ROCC the actual scenario prepared in SEROM. It was particularly impressive the precision at which the tools allowed to estimate ramps inclinations together with size of obstacles and terrain slopes at egress routes ahead. At a certain point the ROCC understood that a rock was hidden under one of the ramps (without actually seeing it) and could also estimate the size of the step gap at the edge of the ramp. On top of that having a dynamic model of the rover and lander system and being able to simulate the dynamics of the egress in the 3DROV environment together with the imported DEM data was an additional feature and valuable check to perform before deciding on a egress direction. It is also important to mention that not all the features that were provided by the SW tools were fully automatized, and sometimes required to spend some time manually setting parameters to fit the TM. The process of importing and projection of DEMs and images could be improved by automatic processes.

6. CONCLUSIONS

This section gathers the lessons learnt from the test campaign and gives the first details on the coming activities planned for the near future in the scope of remote rover operations.

6.1. Lessons learnt

This sections summarises the lessons learnt of the test campaign:

- **Big organisation effort**: The test requires a big effort in organisation. Furthermore testing (dry runs) should be planned in advance in order to avoid last minute debugging.

- **Participants roles assignment**: It helped significantly having assigned roles to participants. Everybody focused on their task and the test could be executed within the planned time. Also the Test Manager team showed to be instrumental in orchestrating the test.

- **End-to-end setup validated**: The setup was considered to be appropriate for the rehearsal of end-to-end system operations.

- **Rover instrumentation for Egress**: the tests confirmed the adequacy of rover instrumentation and of ROCC TM processing tools (**3DROCS**) to enable safe Egress operations. The risk evaluation was very accurate with significant situational awareness. It also show the relevancy of the IMU data as starting point of risk evaluation.

- **Panoramic view**: All participants agreed that a 360 panoramic view was very useful to increase the fidelity of the risk assessment. Therefore the case of not deploying the mast when egressing backwards seems to be more unlikely to happen.

- **Rover characterisation**: The fact that the rover capsized once shows this can happen. However, this could have been avoided if the stability envelope and step clearance of the rover was properly characterised.

- **Enabling deployment actuators (Wheel Walking)**: This also made the case for the actuation of the deployment motors. The rover stability is increased and capsizing could be avoided.

- **Dynamic simulator**: 3DROV dynamic simulator actually advanced the rover would capsize. Even though the terramechanic models cannot be fully trusted it also proved the value of this tooling.

- **Mission timeline**: It was hard to respect the nominal mission timeline with the allowed communication slots. The time needed for the ground decision process in this compressed experiment might be revisited after all the identified gain of efficiency (e.g. addition of some automatic processing - see below) will have been factored in.

- **Automatic import of TM data**: On the other hand the time to process the TM data could be significantly reduced by automating the import processes as well as the estimation of inclinations (lander, ramps, slopes,). Participants also pointed that having a scaled down mock-up of the rover/lander system would help assisting the discussion at the ROCC.

- **Decision making process Check List**: The check list was found very useful to focus on specific tasks in the ROCC and provide a repeatable and consistent procedure for safe Egress.

- **Backup for communications**: A backup solution for communications between Rover and ROCC should be established to avoid the use of standard email at the test campaign.

- **Backup for rover localisation**: During the test we suffered various GPS LoS. An alternative rover localisation scheme should be guaranteed.

- **Non-nominal cases**: Most interesting experience and feedback is obtained when exercising non-nominal cases. Pushing the limits of the system is the way to acquire fast and relevant expertise on remote rover operations.

6.2. Follow-on Activities

After this successful test campaign further tests have been planned to exploit the remote rover operations concept in the context of the upcoming ExoMars rover mission and also to increase the collaboration between the agencies. At the time of publication, a 2nd test campaign in CNES is foreseen for May 2016 where the main objectives will be to consolidate the tools and procedures of the first test campaign by repeating one Egress manoeuvre and then continue by performing first sols of operation in Mars.

ACKNOWLEDGMENTS

Authors would like to give their acknowledgement to all entities participating in the test preparation and execution. Starting from members of the TEC-MMA section to colleagues in the ExoMars Team (ESA internal and industrial partners TAS-I, ALTEC and TRASYS) as well as collaborating agencies, ESOC mission operations group and last but not least CNES robotics group that hosted the field testing team in their premises and gave us unconditional support throughout the campaign week.

REFERENCES

[1] M. Woods et al., *Seeker - Autonomous long range rover navigation for remote exploration*, iSAIRAS 2012.

[2] ESA SAFER Project, online $http://www.esa.int$

[3] P. Steele et al., METERON OPSCOM-2 Science Report, 2014.

[4] P. Poulakis et al., *3DROV: A Planetary Rover System Design, Simulation and Verification Tool*, iSAIRAS 2008

[5] K. Kapellos, K. Wormnes, L. Joudrier, *3D Rover Operations Control System: application to the ExoMars mission*, iSAIRAS 2014

[6] Martin Azkarate, Technical Note on *Test Plan for Remote Rover Operations Field Testing Campaign in CNES*, 2015.