# THE LUCID FIELD TEST CAMPAIGN – RESULTS OF OPERATIONS WITH A ROVER IN A SIMILAR LUNAR ENVIRONMENT

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## ABSTRACT

The goal of LUCID (LUnar scenario Concept valIdation and Demonstration) was the evaluation of a complete suite of sensors and techniques to operate a rover in a lunar polar scenario. This project is a consequence of the growing interest on lunar South Polar Region exploration, due to the new orbital data acquired in the last years.

Every sensor and technique integrated on the Field Test Rover (FTR) had already been described in [1]. This reference offers detail on all relevant rover systems and their main characteristics; it included sensors, localization techniques, terrain reconstruction (DEMs generation), locomotion, details on the software suite based in ROS and developed by GMV, and the local and remote control consoles used for operations planning and execution.

The present paper briefly recalls major LUCID system facts and presents a review of the results and conclusions of the two field test campaigns performed. The objective of the tests was to answer the following: what does it take to operate a rover in Lunar near-pole conditions? What is the best situational awareness that can be implemented with present-day technology? How far can a rover traverse under these conditions per unit of time?

## 1 INTRODUCTION

Interest in the Lunar South Polar region has grown significantly within the international exploration and science community in recent years, fuelled by the abundance of new orbital data acquired by the fleet of orbiter missions sent to the Moon during the past decade. As part of a broader lunar exploration effort, ROSCOSMOS and ESA strive towards the Lunar Polar Sample Return mission. In this context, the objective of LUCID (LUnar scenario Concept valIdation and Demonstration) is to assess the combination of tools and techniques required to operate in the environmental and operational constraints of the polar lunar environment. Focusing our efforts on the Situational Awareness Techniques, GMV robotics team designed a Field Test Campaign to be carried out in the terrestrial analogue of the Lunar South Pole at Teide National Park located in Tenerife, Spain. In this location, tests addressed particular challenges such as the low angle illumination, representative communications, terrain characteristics, simulated ice sources [5] and observability of the surroundings for both operational scenarios: short term autonomy and teleoperation. As part of the activity, a software suite based in ROS was developed to cover all the necessities of the field Test Campaign that comprises the FTRS (Field Test Rover System), the Remote and Local Control Consoles.

*Figure 1: FTR at Minas de San José. P.N. Teide, Tenerife.*

## 2 MISSION SCENARIO

Due to the relative inclination of the Moon orbit with respect to the ecliptic, direct line of sight teleoperation is only available during half of the moon phases.

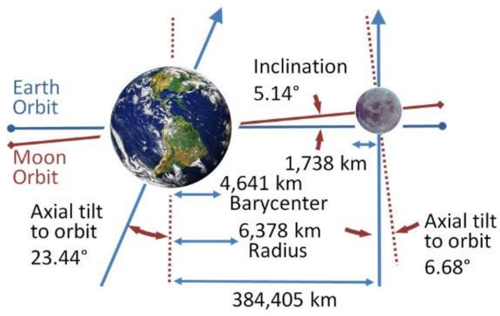


*Figure 2: Earth - Moon relative orbits*

This situation yields to a mission scenario in which teleoperation with 1.3 seconds delay is available during half of the Lunar period, and communications through a relay satellite, with passes each two hours, is mandatory for the other half of the period. Therefore, the LUCID field test campaign studied two scenarios:

● Teleoperation: limited bandwidth and 2.56s round-trip delay for communications.

● Autonomy: operations cycles of 2 hours with communication windows to the Remote Console of 10 minutes.

For each of these scenarios, the study was focused on how different situational awareness techniques were able to help the operations.

## 3 SITUATIONAL AWARENESS TECHNIQUES

In this section, we review the different Situational Awareness sensors mounted on the rover in relation to the techniques implemented:

**Hazard Cameras (IMAGING-1).**

The FTR mounts three Hazard cameras. Two of them at front corners and a third rear camera placed at the centre of the back side of the FTR deck. They are placed on top of the rover deck, attached by means of small brackets and pointing slowly downwards.

The three cameras mount the same lenses (175º fish eye). The fish eye lenses provide a very wide view angle covering the surroundings of each of the rover wheels. It makes them very useful to assess that locomotion performs safely, especially in hazardous areas such as narrow corridors and surfaces plenty of obstacles. Their function cannot be replaced by other imagers since they are the only ones that provide a direct view of the wheels and their surroundings.

**XB3 stereo camera (IMAGING-2 + SDEM-2)**

The Bumblebee XB3 is a stereoscopic pair mounted on top of a Pan & Tilt Unit at the front mast of the rover. It allows performing both, photogrammetry (short DEMs generation) or displaying single images from one of the cameras.

Since it is placed on top of the front mast, it provides a point of view similar to what a standing human would get at the FTR position. The XB3 Field of View is around 43º, which is slightly narrower with respect to what is considered the standard human Field of View. Consequently, it provides views that are naturally interpreted by the operator and that, at the same time, serve to perform accurate distance and size estimation due to lower optical distortion.

SDEM2 technique provides Short Range DEMs from pictures captured by the XB3 stereo pair. The processing chain is based on algorithms from the libelas library (ELAS: Efficient Large-scale Stereo). It works particularly well with low textured images such as the ones obtained at Minas de San José and the ones expected to be found in soft-soil areas from the surface of the Moon. It was effectively tested along both phases of the Test Campaign at Minas de San José. In fact, no major problems to perform the matching process and produce the disparity images were found.

**BB2 stereo camera (IMAGING-22 + SDEM-22)**

The BumbleBee2 is a stereo-pair camera placed directly on top of the rover deck. It is mounted looking to the front and slightly downwards. The main purpose of this sensor is performing several photogrammetry tasks (monocular and stereo odometry and generating terrain Short DEMs).

This camera provides relatively narrow views of the immediate (front) surrounding of the FTR but without covering the immediate proximity of the wheels. In terms of area covered it overlaps with the wider views from front HAZCAMs, although the images provided are almost lacking distortion when compared to the fish-eye views from the last ones. It allows a more accurate estimation of the size of close objects and terrain features. The processing shares the same pipeline than SDEMs from XB3 camera. Thus, it shares also the good performance in the testing conditions at Minas de San José.

**LadyBug2 Panoramic Imager (IMAGING-3)**

The LadyBug2 panoramic imager is a camera system composed of 6 single cameras: 5 cameras pointing horizontally and equi-spaced covering 360º space and one camera pointing upwards.

The LadyBug2 was basically used in single-shot mode along the campaign for communication efficiency reasons. It means that the operator requested a single panorama, then the 6 pictures were taken at the FTR side and sent to the Control Station, where they were stitched and presented as an interactive spherical image. The operator could then interactively (mouse dragging) select the viewing direction inside the spherical panorama.

**Time Of Flight (TOF) Camera (SDEM- 1)**

The SDEM1 technique provides Point Clouds and Short range DEMs built from raw measurements of a TOF Fotonic E70 camera. This camera is mounted on top of the Pan & tilt Unit at the front telescopic mast. It has a field-of-view coverage of 53º (vertical) x 70º (horizontal) being able to acquire an image of 160x120 pixels with an accuracy of ±10mm up to a distance of around 2m and accuracy of ±30mm up to a distance of 7m.

**GEPE camera experiments (SDEM-3, with stereo-projection system and LDEM-1)**

For the realization of both techniques, the Geometric PanCam Emulator (GEPE) developed by Joanneum Research was used. GEPE is a prototype of the ExoMars PanCam to simulate, study and test geometric issues. GEPE includes two wide angle cameras of 38° FOV and 5MP for multispectral stereoscopic panoramic imaging.

The GEPE system was designed to work with or without a laser pattern projector (depending on lighting conditions). For the laser pattern projection case an automated pattern alteration device was implemented (a rotating prism inside the projector changes the point pattern). For each data acquisition a certain number of different point patterns are recorded by the stereo pair. The images are then combined before the actual stereo reconstruction workflow is performed.

*Figure 3: GEPE with pattern projection system at work in Minas de San José.*

The second scenario is based on GEPE camera also and relies on the rover artificial illumination system. For this technique no image stacking for DEMs generation is necessary (just need for one image pair per region scanned).

**RE05 LIDAR (LDEM5)**

The Ocular Robotics RE05 sensor produces dense Point Clouds (natively they cover 360º) but due to placing limitations, there is the need to filter areas obstructed by other elements on top of the FTR. According to the manufacturer specification, the RE05 is able to cover a range of 30 m with reflector-less surfaces (this is the case of the Minas de San José terrain properties) and up to 160 m with high reflectivity targets. The accuracy of RE05 depth measurements is in the order of ± 50 mm, which is a considerably good resolution when considering the range.

The DEM generation algorithm within LUCID activity implements a ROR (Radius Outlier Removal) filter which removes points that are not likely to produce usable DEM surfaces. It reduces the range of produced products below 30m, since the density of the Point Clouds generated is lower at far distances of the FTR and thus, most of the outliers are found at far range.

**Velodyne VLP-16 LIDAR (SDEM-3)**

Velodyne VLP-16 is a far range 16-lines scanning LIDAR with a limit range around 100m. Since it provides sparse Point Clouds (only 16 horizontal lines are scanned at a time) but is able to perform the measurements in a short time, the most convenient strategy was performing concatenation of several PCs while the FTR moves. It allows building a denser mapping with a sensor that in fact provides sparse mapping.

## 4 TEST CAMPAIGN SUMMARY

The LUCID Field Test Campaign was performed at Minas de San José, in Parque Nacional del Teide, Tenerife (Spain), along two different periods in June and October 2017. Each period lasted for two weeks and all tests were performed during night time. Some of them also included a low-elevation Sun lighting emulator.

This National Park provides several Mars and Moon analogue areas (see [2], [3] and [4]). Its good and stable weather based above the cloud base, easy accessibility by car, minor restrictions to access, good terrain traversability, good analogue lithologies to test tools and analytical equipment, good accessibility to volcanic outcrops by rovers and little vegetation cover make it and ideal place for LUCID. More specifically, from a geological perspective, it is important to stress that Las Cañadas Edifice is the major central volcanic complex of Tenerife and it was built on the remnants of the Old Basaltic Series.

The split in two phases was a consequence of several logistics problems happened before the start of the test campaign in June. Despite the over-cost of splitting the FTC in two phases it has demonstrated technical advantages such as the possibility of applying lessons learnt and maturing some systems and procedures for the second phase.

The Test Campaign was organized in the following way: Specific and reduced Situational Awareness tests were carried out along Phase-1, while complete Mission Tests both in Teleoperation and Autonomy mode were carried out along Phase 2.

*Figure 4: FTR performing Point Turn at Minas de San José.*

During the time in-between the two phases, the lessons learned from Phase 1 were used to improve some of the FTR systems.

Data from table below help to understand the importance of data collected and the amount of work performed along the test campaign. It contains the main metrics (cumulative) corresponding to all tests performed along both phases of the Test Campaign. From the point of view of the amount of information collected, and the amount of experiments performed the campaign was a success.

| Metric | Value |
|---:|---:|
| Total Test time logged | 46 h |
| Total distance travelled | 4663 m |
| Mean distance travelled per hour | 103.62 m/h |
| Total size of images transferred | 50.66 GB |
| Number of Point Clouds requested | 232 |
| Total size of Point Clouds requested | 848 MB |
| Number of DEMs requested | 129 |
| Total size of DEMs requested | 2.83 GB |

Given the total log time and distance travelled, the effective distance travelled per hour was 103.62m/h. Assuming that when the FTR moves, it is doing it close to 0.1m/s (the maximum FTR speed), the analysis of the previous data showed it was moving around one third of the total Test time.

Although the low FTR speed was clearly a limitation from the point of view of the number of different areas and terrain features that can be visited along one single Test, it is, on the other hand, close to the real capabilities of the planetary exploration vehicles (e.g. the specification for Curiosity was a maximum effective speed of 90m/h when using automatic navigation but it was expected to travel at a mean of 30m/h).

## 5 TEST RESULTS

The first aspect to consider with respect to the evaluation of the Situational Awareness techniques was whether the techniques available and localization solutions for each Test allowed the operator to fulfil the objectives of each scenario and in which conditions there were severe difficulties for that.

The situations considered as a fail to fulfil the mission objective of the test were the following ones:

● The operator completely fails to find the way to arrive to the target point or to follow the pre-defined path or to find (simulated) ice sources due to lack of information about the environment or about the rover.

● There was a critical risk to the system and the rover had to be stopped by means of the emergency button.

● The rover gets stuck in an area without the possibility to go out from that area without compromising the safety of the FTR.

According to these criteria, there were only a few percentage of tests that failed to fully accomplish the mission objectives specified by the Test. The analysis of these tests was very useful in order to assess the conditions in which a mission can be lost and to identify key information required from SA techniques.

| Id. | Cause of the fail |
|---:|---:|
| 1 | Emergency button is activated because of probability of hitting a rock to the left. The test area is very difficult (high density of small rocks inside a crater) and the operator is tired after other tests the same night. In addition only one HAZCAM (right) was active at that moment. |
| 2 | Rover enters into a dangerous crater. Emergency stop after entering into a crater with high slope, which was not in the nominal route to be followed. It seems that the large localisation error in combination with the very scarce SA information available could have played a role into that. |

| | |
|---|---|
| 3 | Emergency stop. The safety man had to stop a LOMT command in Autonomy mode. It is due to an incorrect assessment of the distance to be travelled. |

The analysis of the information summarized in the table above, highlights several factors that, in combination, are able to risk the success of the mission:

● Operator fatigue (after several hours of operation).

● Extreme difficulty of the terrain to be traversed (normally in combination to scarce SA means).

● Very poor localisation solution.

● Very scarce SA resources or not adequate for the task (e.g. using only one HAZCAM to travel through a corridor with obstacles at both sides).

● Incorrect assessment of the distance to be travelled in interactive autonomy and lack of collision avoidance function in the autonomy layer.

● Errors in the command formatting.

In the next paragraphs we analyse the results of the test campaign for each group of Situational Awareness or Localisation techniques.

**Imaging Techniques Evaluation**

Tests performed along phase 1 of the Field Test Campaign (June) in Minas de San José (Tenerife) were specifically target to reduced SA combinations in order, first, to determine whether operation tasks could be safely performed in these conditions and second to assess strengths and limitations of each specific technique and the best way to combine and use them along a mission.

Images coming from the different FTR cameras were mostly acquired and sent to the GCS as image streams, except in the case of the LadyBug2 panoramic imager, for which single shots were taken, sent and assembled at the GCS side on operator demand.

HZCAMs (IMAGING-1)

Despite the great advantage of the use of 175º fish eye lenses, they have also their counterpart. It is related basically to the lenses lack of optical distortion correction in order to cover that wide angle. It causes that accurate estimation of distances and sizes is very difficult for the operator, especially with objects present at sides and corners of the image. It makes also difficult the accurate use of visual aids on top of images displayed at the Control Station, since the standard camera pinhole mathematical model is not accurate enough to provide good distance estimations.

Nevertheless, image streams from some of the front HAZCAMs has demonstrated to be basic for many sections of the traverses performed. The rear HAZCAM was much less used but it is key to assess safety of the rover Point turns when in areas plenty of obstacles, since once the FTR passed close to an object and is no longer in the images of the front imagers it is difficult to determine how far the rover is from it.

*Figure 5: Front Right HAZCAM view*

XB3 and BB2 images (IMAGING-2, IMAGING-22 and IMAGING-3)

Compared to the HAZCAMs, the Field Of View of XB3 and BB2 is too narrow to allow full SA of the rover surrounding environment. In fact, the Field tests demonstrated that the operator had to frequently complement the frontal views from XB3 with LadyBug2 panoramas or with DEMs to improve SA of the rover surroundings.

Nevertheless, the image streams from XB3 have demonstrated to be a perfect mean for continuous teleoperation in relatively easy areas, and also in difficult ones complemented with other sensors.

A potential alternative to the LUCID configuration would be using a panoramic imager of the type of the LadyBug2 with the possibility to provide only frontal views (operating as an equivalent to the XB3 views) or providing stitched panoramas to gain SA of the rover surroundings.

Regarding the Pan & Tilt capability, it demonstrated to be useful (e.g. concatenating several SDEMs) but it was not used so frequently as expected probably due to the additional time required to operate it.

BB2 single images have been requested in very few occasions along the Field Tests due to its low Point of View. On the contrary it has demonstrated to be an interesting type of sensor for accurate visual odometry (LOC5 technique) when used in stereo configuration.

Panoramic images demonstrated to be a very useful SA technique for general awareness of the FTR location, showing the FTR surroundings up to the limit of the artificially illuminated area.

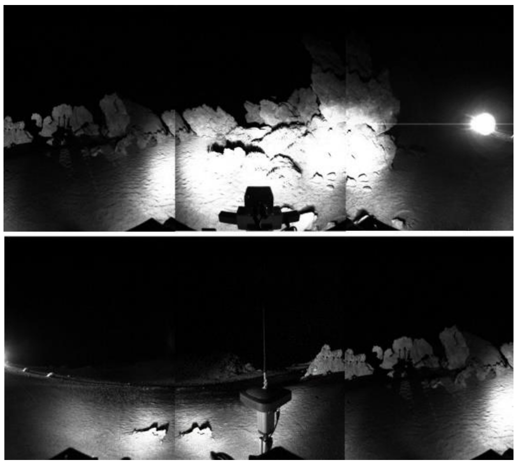

*Figure 6: LadyBug2 panorama*

It requires from wide angle lighting when the FTR is inside shadowed areas, which is costly in terms of electric power required. In a real mission this problem may be overcome by only switching-on the lighting system at the moment of exposing the images. The Field Test Campaign has demonstrated that operation efficiency quickly raised from the moment panoramas were available (the first SA technique specific tests were performed without panoramas available). Indeed, one of these tests without panoramas failed to meet the main objective and the FTR got stuck inside a crater due to very scarce SA resources.

**Localisation techniques evaluation**

Several localization techniques were also tested at Minas de San José. All of them performed hybridization of several measurements by means of different filters of the Kalman family ([6]). LOC5 technique demonstrated to be the best performing one. This technique included stereo visual odometry measurements from BB2 stereo pair (low point of view), in addition to the basic set of raw measurements (IMU, FOG gyroscope and wheel odometry).

In LOC5, the visual odometry algorithms (from Spartan activity) work under very good conditions due to the shorter baseline (less discrepancy between frames) of BB2 pairs and its higher acquisition frequency (compared to XB3 pairs).

Table below shows a comparison between performance metrics obtained for the basic LOC1 technique (no visual odometry) and LOC5.

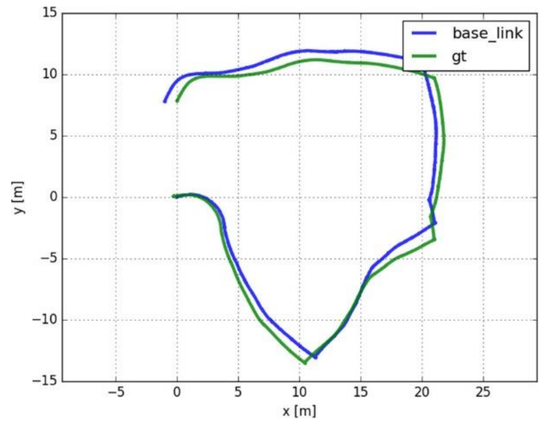


*Figure 7: LOC5 localisation solution v.s. ground.-truth*

| | LOC1 | LOC5 |
|---|---|---|
| Mean Abs. Error [m] | 0.62 | 0.46 |
| Max Abs. Error [m] | 1.66 | 0.97 |

**Short DEM techniques evaluation**

The resolution of depth images provided by the TOF camera was low compared to those from stereo pairs. Nevertheless and due to this fact the DEM generation process was very optimized, the processing time to get back the product (SDEM1) was quite short (< 1min) and the Tests have demonstrated that the operators feel comfortable about requesting this type of product when needed to evaluate terrain slopes and other close terrain characteristics (see Figure 8).

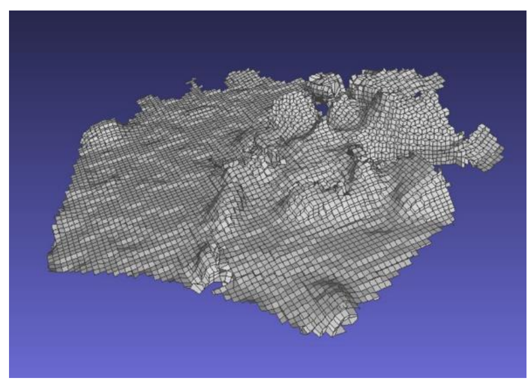

*Figure 8: SDEM1 product (from TOF camera)*

On the other hand, SDEM2 products (which also include overlapped texture images) demonstrated to be very useful for numerical evaluation of slopes to be traversed as well as some very specific terrain features in front of the FTR (e.g. small crevasses).

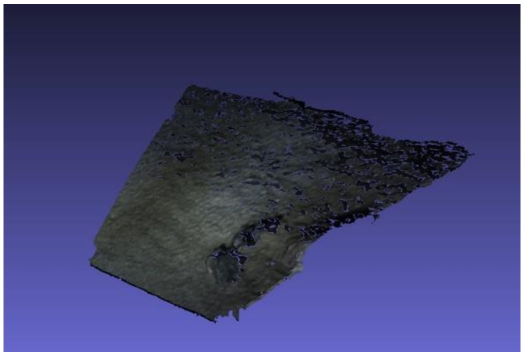

*Figure 9: SDEM2 product (from XB3 camera) textured with colour pictures*

DEMs with overlapped texture (monochrome) from BB2 images, were also consistently obtained along the Tests performed. Main differences with respect to DEMs produced from XB3 stereo pair are the lower view point and consequently a more reduced range and covered area. In this case, the DEMs are enriched with the B&W textures from BB2 cameras. As, happened with SDEM2 technique, the processing time is considerably larger than in the SDEM1 technique (TOF) due to the need for running the full image processing chain including all image conditioning, matching and disparity image generation processes. Nevertheless, the time to retrieve this product is still under reasonable limits. They demonstrated to be useful to assess slopes and to investigate terrain features very close to the rover.

<u>GEPE Camera experiments</u>

Both GEPE configurations (with and without laser pattern projector) demonstrated to contribute to overall SA of the FTR. Both can support the operator in teleoperation mode in choosing the right path, especially when very fine terrain resolution is required. The results can be the basis for automated hazard detections, terrain analysis and pathfinding for autonomy scenarios as well. The effects of very fine-grained lunar regolith on direct illumination without pattern could not be tested due to the relatively coarse grain size of the Minas de San Jose area. The choice between them highly depends on development possibilities in an energy saving light source, mounting possibilities for said technique and time constraints.

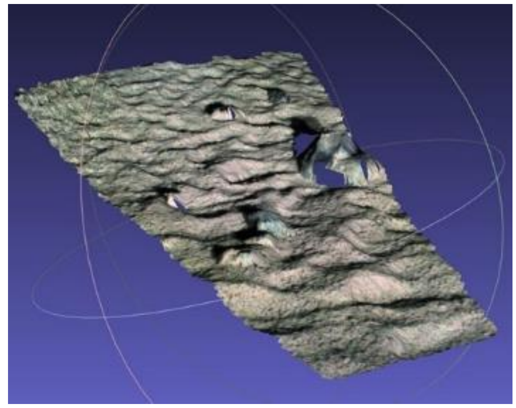

*Figure 10: GEPE LDEM1 products*

**Long DEM techniques evaluation**

The dense Point Clouds from the RE05 sensor demonstrated along the campaign to provide a high amount of information for the FTR surroundings. The enrichment of the Ground Control Station 3D Plan Editor (see Figure 12) with raw Point Clouds turned out to be very useful and most of the time there was no need to request for the post-processed DEM. The advantage of Point Clouds is that the operator does not need to wait for the additional processing time of the raw data. On the other hand, the DEM products allow measuring distances and size of terrain features. Proper measuring of distances has demonstrated to be key in the Autonomy scenario. In the teleoperation case, panoramic images generated with good lighting conditions could replace somehow the information at medium range provided by Long DEMs but for the Autonomy scenario the availability of Long DEMs is key.

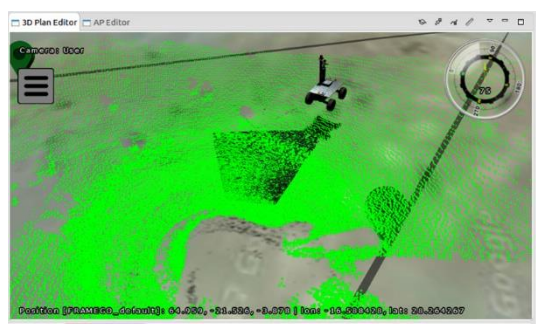


*Figure 11: Several RE05 Point Clouds on the 3D Plan editor*

The tests run along both phases of the FTC confirmed that the VLP-16 sensor was also able to provide good quality Point Clouds at distances close to the manufacturer specification (100 m).

Since VLP-16 provides sparse Point Clouds (only 16 horizontal lines are scanned at a time) but is able to perform the measurements in a short time, the most convenient strategy was performing concatenation of several PCs while the FTR moves. It allows building a denser mapping with a sensor that in fact provides sparse mapping. As a counterpart, accuracy of the concatenation depends on the performance of the localization solution, thus causing the maps to deform and drift with the localization error. Nevertheless, it only demonstrated to be a problem in tests in which the localization solution drifted strongly due to some problem. In this case, it was needed to clean the previous Point Clouds buffered and start again the concatenation.

In the same way, the generation of DEM products required from the concatenation of several PCs generated during rover locomotion. The quality of these DEMs is dependent on the number of PCs and on the accuracy of the localization solution available.

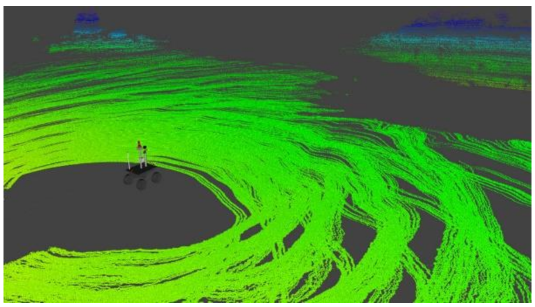

*Figure 12: Several VLP16 Point Clouds concatenated*

## 6 CONCLUSION

Overall success of the FTC at Minas de San José is clear from several points of view: the large amount of information gathered from a considerable amount of effective test hours as well as the variety of experiments and Mission Tests run.

From the point of view of the Field Test Campaign organisation and despite the over-cost of splitting the FTC in two phases, it demonstrated technical advantages such as the possibility of applying lessons learnt and maturing some systems and procedures for the second phase. The split in two-week periods seemed also to be convenient from the point of view of the Test Team work-load and required resting periods due to the hard working conditions during the nights.

Test metrics show significant variability coming from multiple factors that are difficult to decouple and to individuate without a very large number of Tests (much more than was possible to execute along the 4 weeks of Testing). Despite of this fact, the critical analysis of the largest set of similar Tests performed (Mission Teleoperation Tests) is able to confirm that both Operator and type/difficulty of Terrain traversed has an impact on the amount, type and quality of SA information required to meet Test objectives.

The overall effective distance travelled per hour was 103.62m/h. Taking into account the fact that FTR moved most of the time close to 0.1m/s (the maximum FTR speed), it implies that FTR was moving around one third of the total Test time.

In addition to pure statistical analysis of Test metrics, the operator and external observer evaluation of the experiments were demonstrated to be key to improve SA means, especially when referred to presentation of the information and usability issues.

It is confirmed the usefulness of the FTC to improve the GCS usability and mature the overall FTR system. In addition, reduced or degraded SA Tests confirmed to provide interesting insight into the identification of factors and combinations of them (or required degree of problem severity) that can lead to Mission fail.


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