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METERON Analog-1: A Touch Remote

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Abstract

The METERON project (Multipurpose End-To-End Robotics Operations Network) was implemented by the European Space Agency as an initiative to prepare Europe for future human-robotic exploration scenarios that in particular, focused on examination of the human-robotic partnership, and how this partnership could be optimized through an evaluation of the tools and methodologies utilized in the experiments in the domains of operations, communications and robotics (specifically with respect to control strategies).

Implemented through series of experiments of gradually increasing complexity, the project was originally conceived to culminate in the control of a rover-robot located at a terrestrial analogue site. Being operated by a geology-trained astronaut from the International Space Station (ISS), such a test would enable a reasonably high-fidelity examination of how crew on an orbiting vehicle around the Moon or Mars could remotely perform exploration tasks in an unstructured environment.

In early 2019, Lanzarote was selected as the terrestrial analogue site due to its lunar-like terrain coupled with the fact that the Tinguaton area had been used by the European Astronaut Centre's PANGAE astronaut training course in 2017. Alignment of ISS planning with the logistics planning needed to get all the required infrastructure to Lanzarote in a timely manner eventually drove the team to decide to split Analog-1 into two segments: control of the rover/robot from the ISS, together with a more extensive testing programme at a different site - Mt. Etna in this instance.

The Mt. Etna test will be performed in cooperation with the DLR ARCHES campaign in June-July 2022 as through implementation of a joint 'space demo mission' – described in detail in a companion paper in this Congress – addressing geology and radio astronomy.

The first part of Analog-1 was successfully accomplished in November 2019 by Luca

Parmitano who drove the rover at an ‘indoor’ analogue site in the Netherlands and operated the rover’s robotic arm using a novel haptic control station (Sigma-7) that allowed Luca to ‘feel’ the forces experienced by the robotic arm as he collected selected samples.

This paper will report on the results of the Mt. Etna 2022 campaign and contrast with the results from the ISS experiment obtained in 2019, with a particular focus on the interaction between the ‘Science Backroom’ and the subject astronaut, who for the Etna testing was retired ESA astronaut Thomas Reiter - who had also undergone ESA’s PANGAEA geology training – the advantage of which was clearly demonstrated during the MIRACLES mission.

Keywords: METERON, Analog-1, ARCHES, human-robotic cooperation, Teleoperation

1. Introduction

1.1 Scope

The original intent for this experiment was to carry it out with an astronaut on the International Space Station (ISS) controlling a rover in a simulated lunar mission at an analogue site located in Tiguaton in Tenerife, Spain. However, due to the difficulty in aligning the schedules for the crew member on the ISS and the transportation of the required equipment the decision was taken to split the Analog-1 experiment activity into two parts. The first part of which has been reported at the Global Space Exploration Conference (GLEX) held in St.Petersburg in 2021 [1,2], whereas this paper focuses on the second part, termed Analog-1 Complete, which took place in cooperation with the DLR ARCHES analogue campaign on Mt. Etna in June/July this year (2022).

1.1 METERON Background

The idea of ‘operator in space’ is a core concept (Figure 1) of METERON which was first considered in an internal ESA Concurrent Design Facility (CDF) study on 2009 [3].

Figure 1: Operator in space concept

The concept focuses on the following three ‘pillars’:

- **Operations:** To act as a testbed, providing end-to-end in-orbit demonstration of potential future exploration operations scenarios involving robots and humans.
- **Robotics:** To validate the concept of real-time bi-lateral control of a robot on a planetary surface, from a zero-gravity platform such as a manned orbiter, by human operators with force feedback.
- **Communications:** To perform further in-orbit testing and validation of novel communication techniques under consideration for future human exploration, such as Disruption Tolerant Network (DTN)** concepts and technologies.

***DTN was successfully utilized in some of the earlier experiments and its efficacy established, but for the Analog-1 case it was an unnecessary complication to an already complex implementation activity.*

The primary objective of the METERON activity at ESA is a European initiative to help prepare for human-robotic exploration of the Moon, Mars and other celestial bodies by investigating robotics, communications and operations concepts and technologies, as well as their interaction as a system [4,5]. Secondary objectives are to identify competences and technologies, build a network of competence fostering cooperation, understand the underlying assumptions in human-robotic interaction and test them through controlled experiments, implement and test a preliminary infrastructure, learn from it and understand the requirements for the mission architecture especially for the Artemis missions involving the Lunar Gateway and potential European Large Logistic Lander (EL3) missions.

Specific key questions addressed by METERON are:

- When, how and why control a robotic surface asset on a planetary body from orbit?
- What is the optimum mix of supervisory control and low-latency teleoperations?

- How are the operations to be implemented in a cost-effective manner.
- Operational considerations such as which tasks are robotic and which human, and what data is needed to support the Monitoring and Control (M&C) of assets from an orbiter, a surface habitat or direct from Earth. Such considerations feed directly into the design and optimization of future data and communication systems.

The above questions were addressed throughout the series if 13 experiments starting in 2012 with the OPSCOM-1 experiment and culminating in the Analog-1 ISS and Etna experiments (see Table 1).

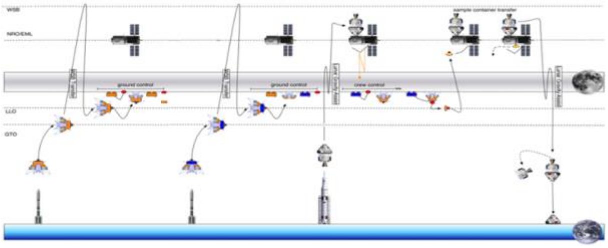
Table 1: Overview of METERON experiments.

Experiment	Description
OPSCOM-1	2011-2012: Communications setup and first demonstration of DTN utilisation for robot control via ISS
OPSCOM-2	2012-2014: Validation of communications and operations systems for supervisory robot control (Eurobot Ground Prototype) from ground and space via DTN
OPSCOM-3	2018-2019: Consolidation of DTN expertise with a focus on the more demanding aspects of the protocol, e.g. video multicasting, routing, etc.
SUPVIS-E	2015-2016: Advanced Supervisory control tests of multiple robots (Eurobot, surveyor) using advanced DTN techniques (part 1: no introduced errors, part 2: with errors, e.g. failed auto grasp)
SUPVIS-M	2016: Control of a rover in Stevenage Mars Yard from ground and space, focusing on rover speed in supervisory vs manual control, in varying lighting conditions (incl. pitch dark).
SUPVIS-JUSTIN	2017-2018: In-flight demonstration of the possibilities of commanding a robot to carry out complex dexterous tasks with significant communication round-trip time. SUPVIS Justin addressed the local intelligence of the robot required to interpret and execute an astronaut's command.
HAPTICS-1	2015-2017: In-flight haptic experiments using a single degree of freedom force reflective joystick, physiological data collection in view of design evaluation.
HAPTICS-2	2015-2017: Teleoperation with force-feedback from space to ground under various protocols, analysis of tactile perception impacts from exposure to sustained micro-gravity, bilateral control with force-feedback under time delays.
INTERACT	2015: Teleoperation with force-feedback from space of a full robotic vehicle equipped with two lightweight manipulators and a camera system to perform a sub-millimeter precision task.
RaCER	2018-2019: Rover Speed Characterisation for Lunar Exploration, test of Surface mobility and manipulation in direct, supervised and mixed control modes in a lunar representative field test.
HOPE-1, HOPE-2	2017-2019: Evaluation of tools and techniques to conduct distributed Lunar surface operations; full immersion of a simulation team in preparing and executing a geological exploration mission; ground analogue testing conducted in cooperation with the Canadian Space Agency
Analog-1	2019 (ISS); 2022 (Etna Sicily): ISS Technology demonstration aimed at assessing the effectiveness of highly intuitive high-DOF on-orbit haptic interface for direct control of a complex surface rover/robot. Evaluation of the interaction between the ground and the astronaut in orbit in the selection of geological samples. Full-fledged mission sequence simulation in an analogue environment.

1.2 The Analog-1 Scenario

The scenario selected for the Analog-1 experiment is a (notional) European Large Logistic Lander (EL3) mission [6] focused on a human-assisted sample return from the Moon. Here, an astronaut located on the Gateway performs a geological sample survey and sample collection via the teleoperation of a robotic asset (rover) located on the lunar surface (i.e., the core METERON scenario).
This scenario was utilized for both parts of Analog-1.

Figure2: The EL3 (notional) sample return scenario for Geo 2



2. Material and Methods

2.1 Analog-1 ISS Summary

The ISS part of ANALOG-1 [1] was aimed at assessing the effectiveness of a highly intuitive high-DOF on-orbit haptic interface to control a complex surface rover/robot.

The on-orbit control station was based on one of the best-in-class COTS haptic device used worldwide in fine motoric/manipulation control (Sigma 7) and was complemented with a second controller allowing the operator to select mode, camera views and rover motion; in addition, a delay-compensation controller was developed in cooperation with DLR which allowed implementing the best delay-compensation controller, to cope with robotic control instabilities caused by variable communication characteristics [7].

The ISS experiment also provided a first-hand evaluation of the interaction between the ground support team and the astronaut in orbit in the selection and collection of geological samples.
The astronaut was trained through the PANGAEA program organized by ESA-EAC.
The science support team were geologists conducting the PANGAEA training; they prepared the geological

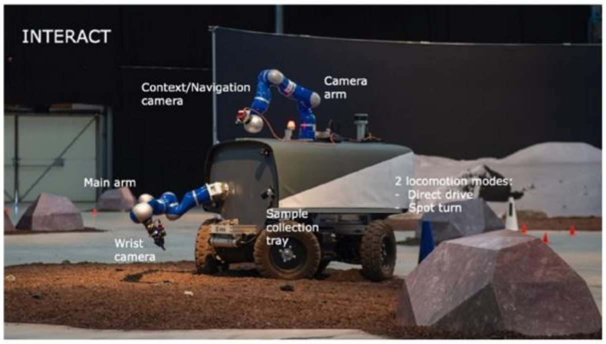
samples and worked with / assisted Luca throughout the experiment.

The experiment was indoor at a test site suitable for conducting the simulated rover driving and sampling on the Moon.

2.1 The Interact Rover

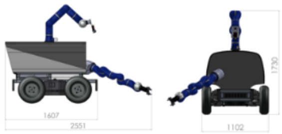
The key element of the Analog-1 activity in both in the Analog-1 ISS and Analog-1 Complete experiments is the Interact rover (Figure 3) which is built around a four-wheel drive platform with cameras and two robotic arms.

Figure 3: The Interact rover.



The arm in the front of the rover is equipped with a gripper and camera end-effector. The other arm holds the main camera (see Table 2 for further specifications).

Table 2: Interact rover specification

Specification	**Value**
Dimensions	
Mobility	Four-wheel drive platform Max linear velocity: up to 0.5 m/s (direct teleoperation) Max turn rate in point-turn mode: 40 deg/s (direct teleoperation) Max steer angle: 25 deg (in waypoint navigation mode) Slopes: The slope limit for the rover in the Etna testing was set to 10 degrees, but the rover, on solid ground can in fact handle much greater slopes
Mobility Control	*Travel and rotate (point turn) via direct teleoperation by orbiter crew* *Waypoint navigation via 3DROCS*
Cameras	*One camera on the tip of the Kuka LWR arm mounted on top of the rover which can be moved to any angle or position the arm can reach by the operator of the ACTOR control station. ACTOR features mode switches to quickly move the camera between a 'sample' preset and a 'drive' preset.* *When operated from the ground the top arm behaves similarly to a pan/tilt unit.* *A second camera is mounted at the tip of the sampling arm.*
Robotic Arm	*The robotic arm is a Kuka LWR arm mounted on the front of the rover which is equipped with a gripper capable of dexterous manipulation through direct teleoperation. Full haptic feedback is transmitted to the operator (reach ~ 80 cm). The end-effector in the scenario was a two-finger gripper.*
Robotic Arm Control	*Direct teleoperation to the orbiter crew with haptic feedback via the ACTOR control station* *A set of pre-defined scripts commanded by an operator to autonomously sample a target of interest*
Sample Cannister	*A sample container is mounted on the front on the rover to receive the collected samples*
Localization System	*The Interact localization system provides real-time localization of the rover with sun-centimeter precision*

Between the Analog-1 ISS and Analog-1 Complete the rover has undergone significant dust proofing to cope with the 'real world' environment of Mt. Etna. The benign environment of the hanger in Valkenburg used for the ISS part of the experiment was much less demanding with respect to dust.

Following the successful completion of the Analog-1 ISS experiment in 2019 [1], an agreement was concluded to integrate the ground test campaign of Analog-1 (i.e., Analog-1 Complete) to the DLR ARCHES campaign planned for the Etna field test site in the summer of 2020, but due to the COVID pandemic, was twice postponed, finally taking place in the summer of this year. A paper reporting on the preliminary results of the DLR-led campaign is reported in [8] at this Congress.

2.1 The ACTOR Control Station

Figure 4: Thomas Reiter (subject astronaut) operating the ACTOR control station.

A detailed description of the ACTOR control station (Figure4) is provided in [1,2].

2.2 3DROCS

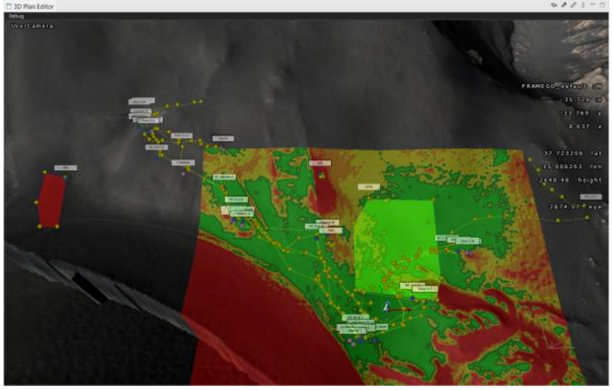
The Analog-1 Ground Control Station is based on 3DROCS [9] that provides an end-to end system for specification, validation by simulation, monitoring, control and assessment of rover operations. Several 3DROCS instances, geographically distributed, are cooperating to exchange and achieve science and engineering objectives. Main functions of the system are briefly described in the following paragraphs.

2.2.1 Situational Awareness

The Situational Awareness is very important feature for safe and efficient planning. The following functions are considered in combination with the 3D visualization of the area in which the rover operates (see Figure 5):

- View Slope Map: the operator may view the complete terrain adirectional slope map.
- Measure Distance/Slope: the operator may measure point to point distances in the 3D scene and may identify the directional slope of a selected area.
- Identify Rocks: the operator may identify if a particular area in the scene shall be considered as a rock for the rover.
- View distances around rover: the operator may measure point to point distances in the 3D scene and may visualize circles around the rover indicating equidistance regions.
- Identify Mast joints to view an area: the operator can identify the joint values of the mast in order to point at a given area in the scene.

Figure 5: the scene is annotated with labels, targets, paths and areas shared by all the 3DROCS instances



2.2.2 3D Scene Annotation – Collaborative Planning

The '3D Scene annotation' functions allow the operator to (see Figure 5 annotations):

- Create/edit targets: the operator creates and edits in the 3D scene Targets that may be used later as parameters to the Activities to be executed by the rover.
- Create/edit areas: the operator creates and edits in the 3D scene Areas of interests and forbidden Areas to facilitate the path planning.
- Create/edit paths: the operator creates and edits in the 3D scene Paths that are used later as parameters to the Activities to be executed by the rover.

This field test campaign is mainly characterized by the presence of several remote-control stations that collaborate to meet the science and engineering objectives. The annotation of the scene with labels, targets, areas and paths stored in a common database endowed with dedicated notification and synchronization mechanisms supported the engineer and science teams to communicate and achieve their objectives.

2.2.3 Control in Interactive Autonomy mode

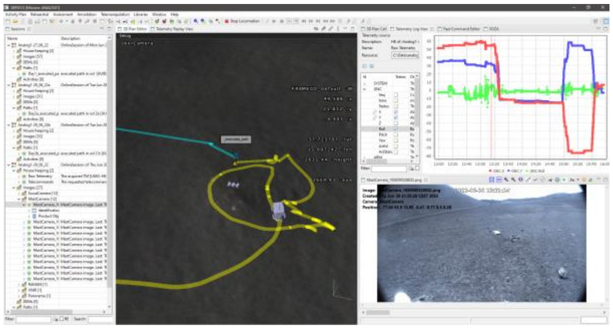
The Activity Execution component allows the execution and supervision of the prepared Activities and Activity Plans. In addition, via the 'Fast Command Editor' the operator has access to the most frequently used Activities with the possibility to set their parameters and request their execution. To facilitate the parameters specification, dedicated areas visualize relevant TM issued by the rover controller. User defined annotations of the 3D scene such as paths and target points may be referenced as parameters and automatically translated into their numerical values.

2.2.4 Data Assessment

The operations are analyzed using the 'Data Assessment' function of the system. It includes (see Figure 6):

- Data Import in Off-line Session: raw telemetry data (HK, Images, Images Stream, Point Clouds, DEMs, Activity reports) are imported and transformed to products for further analysis,
- Initial / Final State Assessment: visualization of the initial and the final states of the system at the period covered by the session,
- HK TM Assessment: visualization on alphanumerical and Chart Displays of the HK telemetry,
- Images Assessment: visualization of the imported images and projection in the 3D scene,
- DEMs assessment: visualization of the imported DEMs in the environment in which the rover operates,
- Executed Path Assessment: visualization of the path the rover executed,
- Activities Assessment: visualization of the Activities executed during the period covered by the session,
- Data Replay: synchronized products visualization in VCR type mode.

Figure 6: The 3DROCS Assessment function



2.3 Analog-1 Complete

The objectives remaining from the first part of the Analog-1 activity are:

Table 3: Objectives of Analog-1

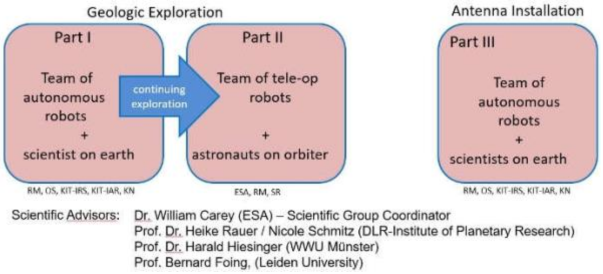
Analog-1 Objective	Addressed in Analog-1 ISS
1: To demonstrate the control of a complex lunar surface rover/robot, specifically relating to dexterous manipulation in performing geological and technical tasks	Fully addressed with the exception of the technical tasks
2: To obtain data on the task duration (navigation, hazard avoidance, sampling, site survey) during a lunar/geology exploration mission, following different strategies and evaluate the differences	Site survey, sampling and navigation addressed, however with reduced representativeness
3: To evaluate the benefits for orbital control versus ground control, by comparing quantitatively efficiency vs time to complete activities as well as qualitatively the operations efficiency	Not addressed as ground control was not included
4: To demonstrate and evaluate the versatility of the developed tools and techniques on rover/orbital control station side by performing tasks in unstructured (geology) and structured (system maintenance) environments	Structured tests were not addressed
5: To further define and evaluate the scientific geological exploration processes, team interactions, timeline, tools and techniques	Addressed, however with reduced representativeness
6: Evaluate the scientific decision-making process during teleoperation in selecting more promising geological samples with the purpose to address defined scientific questions	Fully addressed
7: To further evaluate efficiency of having a geology-trained astronaut	Addressed, however with reduced representativeness

A preliminary assessment of how each of these objectives were met is reported in section 4 below.

2.4 ARCHES Demonstration Missions

2.4.1 Integrated Mission Scenario

Figure 7: The integrated mission scenario



The integrated mission scenario is shown in the schematic of Figure 7, and as is stated in [8] is to investigate how to collectively optimise the operation of rovers/robots using teleoperation, a shared autonomy paradigm and with a high degree of autonomy.

The sequence of events defined by the three individual missions is as follows (and is described in more detail in [8] but summarised here for completeness):

Geo I - In-situ analysis: The first geological scenario focuses on a cooperative heterogenic team of robots, consisting of two wheeled rovers (LRU1 and LRU2) with a flying drone (ARDEA) – three robotic assets - which will fully autonomously explore the site of interest and perform scientifically triggered remote spectral imagery, LIBS (Laser Induced Breakdown Spectroscopy) measurements including complex sample selection, analyses and collection with various robotic tools. The primary focus of Geo I is on the technical demonstration of cooperating autonomous robotic assets, with the secondary objective to demonstrate the end-to-end scientific process of sample selection. An autonomous robotic mission consisting of several robotic assets land on the Moon. These robots have different capabilities, but work together to explore, gather data, and collect samples. This mission occurs prior to the existence of the Gateway, so the rover/robots are operated from Earth, and have certain autonomous functionalities, including a shared autonomous mode involving interaction with scientists on the ground.

Geo II - Sample Return: A few years later a lunar orbiter is deployed in orbit around the Moon, and a second tele-operated mission revisits the original landing site.
The second geological scenario will implement the MIRACLES mission and will focus on the control and coordination of the mission from the Mission Operations Centre (MOC) as well as the interaction and involvement of a geologically trained astronaut to teleoperate a highly dexterous rover with robotic arm while interacting with an operations team and science team on Earth. A fourth robotic asset, the INTERACT Rover will also perform site surveying through supervisory control from a control room at the European Space Operations Centre (ESOC), with the interaction of a team of scientists. A fifth robotic asset, a Scout Rover, will enable an extension of the range of the INTERACT Rover through a coordinated positioning of a wireless repeater. This sample return scenario will address several aspects of visual and haptic feedback, including shared autonomy, to enhance the capabilities of the astronaut's actions to operate the INTERACT rover.

LOFAR: At the same time as the teleoperated Geo2 mission, a robotic mission to deploy a suite of Low Frequency Array (LOFAR) antennas lands in the close vicinity of the other two missions. The installation and maintenance of four antenna sensor array assets, which include a novel technique to measure precise positioning with the use of radio communication as well visual measurements, is to be demonstrated with the two LRU rovers and the ARDEA drone.

2.4.2 Robotic Assets in the ARCHES Scenario

Figure 8: Robotic assets in ARCHES scenario

The robotic assets utilized in the ARCHES demo mission scenario (Figure 8), the details of which are presented and discussed in [8].

2.5 Field Test Site at ETNA

The location of the field test site on Etna is shown in Figures 9 and 10. This location has been used previously by DLR for the ROBEX analogues field test.

Figure 9: Location map of the Analog-1 Complete experiment grounds: left, context; right, the experiment grounds outlined in white

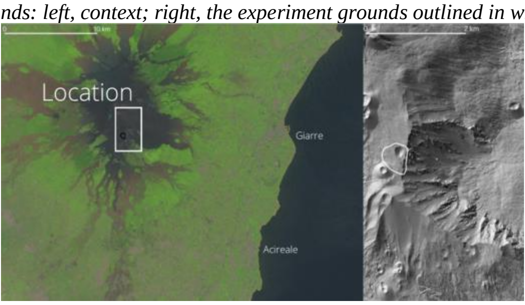
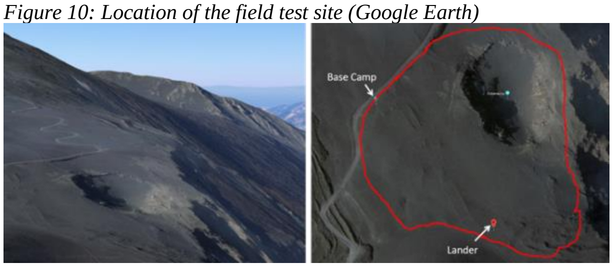


Figure 10: Location of the field test site (Google Earth)

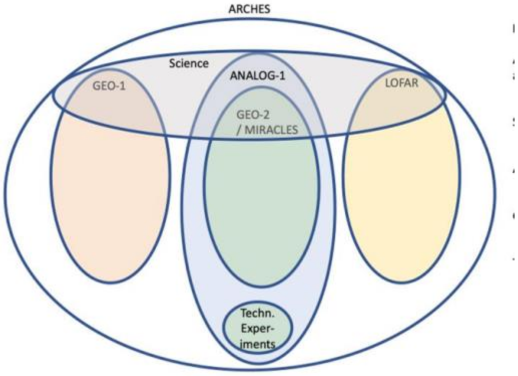


2.6 Science Team

2.6.1 The Scope of the Science Team Activity

The schematic in Figure 11 shows an overview of the three demo missions (Geo 1, Geo 2 and LOFAR) of the overall ARCHES campaign activity and how the science aspects are covered by an integrated DLR/ESA team. The Analog-1 Complete activity addresses the Geo-2/MIRACLES demo mission, and the additional technical experiments which were performed in addition to GEO-2/MIRACLES.

Figure 11: Scope of the science team activity



The science team has been structured in a way to guarantee the preparation of the experiment grounds, its characterization for both science and safety aspects, without disrupting the realistic exploration scenario. This was achieved with the creation of *distinct In-Scenario* and *Out-of-Scenario* teams, respectively performing the exploration with limited a priori information about the site and performing the necessary preparations for implementation of the MIRACLES campaign. The two teams worked independently with the same interface (e.g., data provision for POI/ROI selection)

2.6.2 Out-of-Scenario Team

The Out-of-Scenario Team characterized the experiment grounds and selected samples to be used, together with local ones at Mt. Etna, as representative sample suites for use in relevant POI, chosen by the in-scenario team on the basis of simulated, down-sampled, orbital image data. The Out-of-Scenario team also documented the experiment grounds during and after the mission.

2.6.3 In-Scenario Team

The in-scenario team performed exploration of the field test site on the basis of; i) a small subset of orbital-like data over the experiment grounds ii) live imagery and simulated data provided in real time during operations.

The overall science scenario approach is that of a geologic exploration of an analogue lunar site, based on an increasingly detailed set of robotic and orbital observations [10, 11] (see also Rossi and van Gasselt, 2018; McLennan et al., 2012)

3. Results & Discussion

Table 4: Achievement of Analog-1 objectives

Analog-1 Objective	Addressed in Analog-1 Complete
1: To demonstrate the control of a complex lunar surface rover/robot, specifically relating to dexterous manipulation in performing geological and technical tasks	The technical tasks activities of Analog-1 were performed in this campaign including the additional demonstration of the control of a complex rover/robot and dexterous manipulation
2: To obtain data on the task duration (navigation, hazard avoidance, sampling, site survey) during a lunar/geology exploration mission, following different strategies and evaluate the differences	Fully addressed during this campaign with high fidelity representativeness as the mission was carried out in a 'real' environment
3: To evaluate the benefits for orbital control versus ground control, by comparing quantitatively efficiency vs time to complete activities as well as qualitatively the operations efficiency	Fully addressed in this campaign as both orbital control and ground control were performed
4: To demonstrate and evaluate the versatility of the developed tools and techniques on rover/orbital control station side by performing tasks in unstructured (geology) and structured (system maintenance) environments	Structured testing was carried out successfully in this campaign, i.e., the 'surprise' task of collecting a sample container and returning it to the lander. This was known only to the Out-of-Scenario team and not known beforehand by the astronaut
5: To further define and evaluate the scientific geological exploration processes, team interactions, timeline, tools and techniques	The Etna campaign allowed these processes, team interactions, tools and techniques to be assessed in a 'real' analogue campaign environment
6: Evaluate the scientific decision-making process during teleoperation in selecting more promising geological samples with the purpose to address defined scientific questions	Fully addressed as in Analog-1 ISS experiment, but here in a 'real' analogue environment
7: To further evaluate efficiency of having a geology-trained astronaut	Fully addressed in the high-fidelity Etna analogue environment, so with good representativeness.

The preliminary assessment to which the Analog-1 Complete objectives were achieved are summarized in the right-hand column of Table 4.

The detailed results from a considerable amount of data are still being assessed at this time, but will be published in due course.

5. Conclusions

The ARCHES campaign overall was a significant success with the major objectives of the two demo missions Geo 1 and Geo 2 achieved.

The cooperation between the robotic assets throughout performed to a high level of reliability, particularly between the Interact rover and the Scout rover.

The automatic identification of a rock sample (via AI) and its collection and depositing in the sample container was successfully carried out both by the crew member on the orbiter and from the ground by a science support team member.

Assessment of the GUI used for the experiment was collected through a questionnaire provided to the astronaut immediately following completion of the experiment and is being currently analyzed.

As in the case of the Analog-1 Experiment the advantage of having a geologically trained astronaut was strongly confirmed during this campaign, as the interaction between the astronaut and the science team on the ground demonstrated how this increases the efficiency of the sample selection and collection.

The detailed conclusions from the Analog-1 campaign are still being analysed at this time and will be published in due course.

The successful achievement of the ARCHES demo missions and the combined ESA and DLR science team firmly demonstrated that the cooperation of robots of differing capabilities (i.e., teleoperated, shared autonomy paradigm and high level of automation) can be extremely beneficial – the sum is greater than the parts.

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