



## Research Article

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# ANALOG-1 ISS – The first part of an analogue mission to guide ESA’s robotic moon exploration efforts

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**Abstract:** The European Space Agency’s ANALOG-1 experiment is the culmination of 12 distinct METERON experiments carried out since 2011. These all address aspects of teleoperating a robotic asset from an orbital platform, i.e., technical implementation, user interfaces, autonomy and operations. The ANALOG-1 technology demonstration and operations concept experiment is based upon the surface mission scenario segment of the notional EL3 sample return mission. This segment focuses on the control of a lunar surface robotic asset from the Earth and from the Lunar Gateway. The experiment is taking place in two parts, with the first successfully completed from the ISS in November 2019. It assessed the effectiveness of a state-of-the-art robotic control interface to control a complex mobile robot from orbit, as well as evaluating the scientific interactions, during robotic-assisted geology exploration, between crew in orbit and scientists on the ground. Luca Parmitano operated the robot while he was on the ISS. For this experiment, a complex control station had been installed on the ISS. The experiment demonstrated the advantage of having an immersive control station and high level of robotic dexterity, with Luca finishing all his assigned and secondary geology targets ahead of time.

**Keywords:** robotics, teleoperation, haptics, geology, lunar, moon

## 1 Introduction

In November of 2019 a rover was navigating around a hangar at the old Valkenburg air base in the Netherlands,

near the European Space Agency’s technology centre, ESTEC. It was being operated by the European astronaut, Luca Parmitano, who at the time was orbiting the Earth on-board the International Space Station (ISS). Luca, through this robotic avatar, was navigating around a lunar analogue landscape in the hangar and locating scientifically interesting sites. At these sites he would perform a visual geological survey and select and collect rocks of interest, while in constant contact with a science backroom. Full haptic feedback and an immersive control station installed on the ISS helped the astronaut perform these tasks effectively.

ANALOG-1 is the culmination of the METERON (Carey *et al.* 2012) programme that has been running at the European Space Agency for over a decade. This was the first part of ANALOG-1. The second part of ANALOG-1 will see the rover in an outdoor lunar analogue at Mount Etna, but without involving an astronaut on-board the ISS. This part was planned to happen in summer 2020 together with the DLR’s ARCHES campaign but has been postponed until 2022 due

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**Table 1.** Summary of ANALOG-1 objectives

	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 exception of the technical tasks  <i>Data was collected on the durations associated traversing between sampling sites, description of the sampling site by the crew member, collection and retrieval of the sample, including any incidents of ‘errors’ such as dropping the sample</i>
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, especially in terms of speed of execution/reactivity.	Site survey, sampling and navigation addressed, however with reduced representativeness  <i>Data collected included the specific time of each operation as well as the duration of traverses, interaction with operations teams (about path planning, science context, sampling)</i>
3	To evaluate the benefits for orbital control vs 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  <i>This objective relating to comparison between ground control and orbital control was not addressed in this ISS part of the experiment due to the highly constrained time available for the experiment. However, the data collected may be used as a reference data set to compare with the results of the ground experiment to be undertaken in the summer of 2022 on Mt. Etna, as part of the ARCHES activity (Wedler et al. 2021).</i>
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	Unstructured tasks were not addressed  <i>As with objective 3, the versatility aspect was not addressed, as only data related to the geological activity was collected. Data concerning a maintenance activity, i.e., an unstructured task, was not collected.</i>
5	To further define and evaluate the scientific geological exploration processes, team interactions, timeline, tools and techniques;	Addressed, however with reduced representativeness  <i>Analysis of the data (including telemetry, timing, and traverse path executed) collected by the tools available to the astronaut, e.g., 3DROCS and MOE, together with team interaction metrics (as described in objectives 6 and 7).</i>
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  <i>Data collected here included noting the time and content of the description by the crew member of the sample site (contextual information) through audio recording of the space-to-ground interaction, together with audio recording of the interaction between the members of the in-scenario science team.</i>
7	To further evaluate efficiency of having a geology trained astronaut	Addressed, however with reduced representativeness  <i>The fundamental hypothesis for the scientific part of the experiment was that ‘a geologically-trained astronaut equipped with immersive tools would enable a more efficient and effective interaction with the science backroom on the ground’. Applicable metrics relating to the estimation of efficiency in this regard can be found in Burghart et al. (2008). Questionnaires were also completed by the astronaut and science team members.</i>

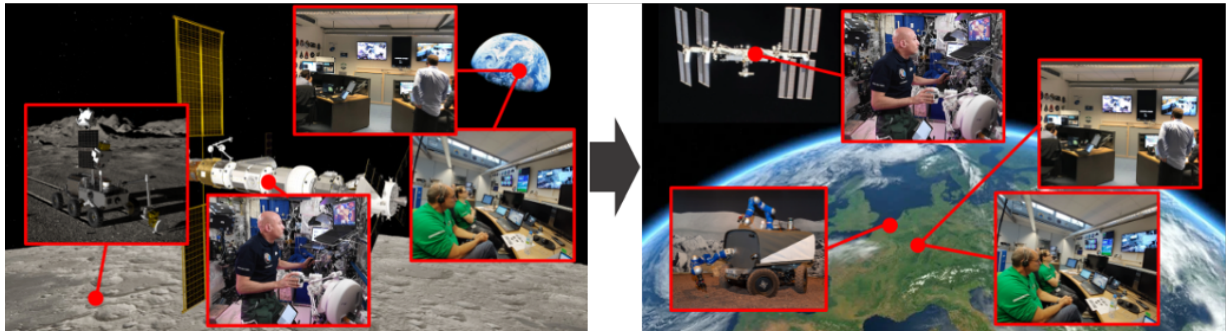


Figure 1. The ANALOG-1 analogue scenario

to the ongoing pandemic. The present paper focuses on the first part of ANALOG-1, referred to as *ANALOG-1 ISS*.

METERON is an initiative to prepare for future human-robotic exploration missions to the Moon, Mars, and other celestial bodies. The project aims to implement infrastructure and tools to test and evaluate communications, operations, and robotic control strategies. It has been organised as a series of experiments that aim to progressively build up the operations of humans and robotic elements combined on a planetary surface. It is in collaboration between three directorates of the European Space Agency (ESA); Human and Robotic Exploration (HRE), Technology, Engineering and Quality (TEC), Operations (OPS).

## 1.1 Objectives

ANALOG-1 built on all the knowledge gained in METERON from the internal ESA study carried out in 2009, through the 12 METERON experiments performed since OPSCOM-1 in 2012 (Martin *et al.* 2013), to the HOPE-1 and HOPE-2 (Gingras *et al.* 2020) experiments of 2017 and 2019, all addressing various aspects of teleoperating a robotic asset from orbit. This included the technical implementation (including qualification for flight of onboard hardware and software), development of user interfaces, the autonomy concepts, operational concept and interaction with scientists.

The primary top-level objectives for the overall ANALOG-1 are summarised in Table 1, where it can be seen that ANALOG-1 ISS addressed many of the ANALOG-1 objectives either partially or fully. The ground campaign in 2022 will fill in the remaining gaps, mainly related to ground operations.

## 1.2 The scenario

Planetary analogue missions are critical to planning real space missions (Groemer and Ozdemir 2020), i.e., they are

essentially ‘fake’ space missions in which the elements that would likely be involved in an actual lunar or Mars mission are replaced by suitably similar analogues. Besides METERON, other related analogue operations have been performed in the recent past at several locations for both Lunar and Martian exploration including for simulated sample return missions (for example Osinski *et al.* 2019). Science operations vary heavily depending on the actual analogue mission objectives and scenarios.

The scenario in ANALOG-1 is based on a notional European Large Logistics Lander sample return mission, in which an astronaut on board the Lunar Gateway is performing a geological survey and sampling by tele-operating a robotic asset on the lunar surface with operational and science support from the Earth.

In the analogue scenario, the Lunar Gateway has been replaced with the International Space station. The lunar surface was replaced by a large hangar, while the operational control (EAC Crew Operations Support – ECOS) and science backrooms were both located at the European Astronaut Centre in Cologne, Germany. This allowed the replication of a similar level of operational complexity, communication requirements and qualification challenges as if having the equipment on the Lunar Gateway but without having the challenges of coordinating an ISS experiment with unpredictable weather at an outdoor analogue site. Figure 1 illustrates the scenario.

## 2 Materials and method

### 2.1 The analogues

#### 2.1.1 International Space Station

ANALOG-1 ISS targeted specifically the ISS Expedition 61 and the Italian astronaut Luca Parmitano. Luca had undertaken geology training under ESA’s PANGAEA programme

(Sauro *et al.* 2018) and one objective (see Table 1) was to see if this training would facilitate communication with the scientists during rock sample selection.

Haptic perception under microgravity conditions can differ from under gravity. This was explored in previous METERON experiments (Schiele *et al.* 2016 and Schmaus *et al.* 2018) but ANALOG-1 extended this to a full 6 degrees of freedom haptic device – something that has never been done before from space to ground. The ISS is the best available analogue we have for the Lunar Gateway as it provides the same microgravity environment, but also has a similar level of complexity in terms of requirements on the communications, security, coordination, environment, safety, qualification, and so forth. The latency involved for the communications between the Earth and the ISS (for the ANALOG-1 experiment) was ~850 ms. This communications link latency will be similar for the Gateway to the lunar surface i.e., ~1 second – so making the ISS a good analogue for the Gateway also in this respect.

These are all factors that significantly complicate an operational experiment like ANALOG-1 compared to doing the same thing with the astronaut on ground, the major differences being the synchronisation of the ISS planning with the ground planning and the considerable effort and time required to qualify the experiment hardware for flight. However, the planning constraints were also a disadvantage of using the ISS. During the time that ANALOG-1 took place there were a number of high-priority Extra-Vehicular Activities going on. As such, there was limited flexibility for when the experiment could be carried out. In an ideal scenario, and indeed in the original plan for ANALOG-1, the rover would be operating in an outdoor geologically representative environment. However, this would introduce uncontrollable risks such as weather that were not compatible with these planning constraints on the ISS. As such ANALOG-1 was divided into two parts, the first part, covered in this paper, addressed the teleoperation from a high-fidelity analogue of the Lunar Gateway (i.e., the ISS), but by having the rover inside a lower-fidelity ground analogue, a hangar. The second part, in 2022, will reverse this situation and make use of a high-fidelity ground analogue, but placing the astronaut inside a lower-fidelity ground-based gateway-analogue, allowing a much greater focus on the objectives related to operations.

### 2.1.2 Valkenburg hangar

Hangar2 at the old Valkenburg air base near ESTEC in the Netherlands was a perfect choice for the ground analogue. Its proximity to the Human Robotics Interaction Laboratory

at ESTEC meant that the logistics of supporting the ground operations were significantly simplified. Also, its size, at 36×60 meters allowed for about 150 meters of traversing and three distinct sampling sites.

The sites themselves were set up as reasonable geological analogues, but without the intention to be extremely lunar-like. Reproducing a lunar visual and geological environment very closely would have in any case probably been prohibitively challenging, and the geological environment will be more representative in the ground test campaign. However, it was sufficient to give the astronaut enough context to stay in scenario while he was describing the site and communicating with the geologists.

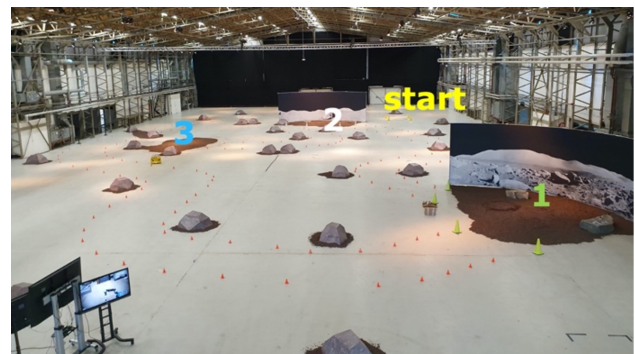
In addition to a regolith analogue, rock-like obstacles were placed throughout the hangar with a navigation path between them marked out with red cones (Figure 2). In a real implementation of the rover control station, one would expect to have navigation aids on screen to help the astronaut choose his route. The red cones played the role of such navigation aids.

## 2.2 Experiment setup – ground

### 2.2.1 Site preparation

All the sampling sites of the indoor analogue environment were set up with typical scoria mantling which is likely to be found close to pyroclastic vents on the Moon, such as at Schrödinger crater. In addition, all the samples placed at each site were both representative of lithologies that can be found in different geological contexts on the Moon and were arranged in realistic scenarios within the limitations of an artificial setting.

In advance of the experiment the samples were placed, and sites were documented both via tagged photographs and photogrammetry. The samples were then removed



**Figure 2.** Hangar2 in Valkenburg set up with three sampling sites and a 150-metre long traverse

again in order to allow further preparations on rover trafficability and operations to be conducted. The sites would be returned to the documented state just before the start of the experiment. This procedure was followed as the placing of the samples at each of the three sampling sites took time to carry out, to document each site carefully and in addition to perform the photogrammetry (which included collection of data using a drone which could not be performed on the day of the experiment itself).

A traverse including three sites with similar morphologic setup and complementary sample variety and arrangement was prepared. The three sites were prepared with a base of pyroclastic loose material of up to a few centimetres thick. Several artificial rocks were then placed on top as navigation obstacles. The real rock samples were added to the sampling sites on the day before the experiment. During the experiment samples were cached and collected from the rover's sample container immediately following the end of the experiment.

The science backroom provided science support throughout the implementation of the campaign. The setup for the science backroom at EAC consisted of a chief geologist and a supporting note taker, in addition to EAC operational staff.

The analysis of the scientific performance was carried out both in real time and using the audio footage of the ISS-EAC interaction throughout the experiment, the video from the rover viewpoint, via its body-mounted camera, and the video from the ISS with Luca Parmitano operating the haptic feedback control system. Audio-video data have been time-registered in order to complete the analysis of the science evaluation and performance. Additionally, the scientist's experience was recorded in an evaluation sheet, completed at the end of the experiment.

The details of the science support to ANALOG-1 ISS has been presented in Luzzi *et al.* (2020).

### 2.2.2 The INTERACT rover

The INTERACT rover (Figure 3) was built by the ESA Human Robot Interaction lab (HRI lab). It consisted of a commercially available, 4-wheeled all terrain AMBOT platform with a custom-made chassis. The chassis had two robotic arms, on each of which a camera was mounted. Inside the chassis were the control computers, a 100Ah Clayton battery and a custom power stage. Power sources were interfaced in a triple redundant configuration to achieve uninterrupted operation while switching sources.

The rover's design protects sensitive equipment against the environment. The chassis can traverse rough terrain

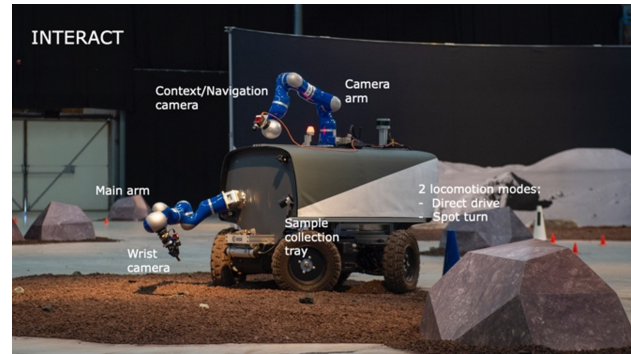


Figure 3. The INTERACT rover

and each wheel can be controlled individually and independently, allowing the implementation of direct drive car-like steering (double Ackerman) as well as spot turn. More sophisticated modes are also possible but were not used for ANALOG-1 ISS.

Of the two robotic arms, one served uniquely as a navigation camera mount that could be controlled by the onboard joystick. The second arm was equipped with a Robotiq 2-finger gripper, a force-torque sensor, and a camera. This arm served as the manipulation system to interact with the environment and handle samples. Its camera was used to provide a more detailed view to the operator when grasping samples. While not a stereoscopic camera, its addition to the navigation camera in combination with haptic feedback allowed the astronaut to confidently move the robotic arm without fear of damaging it.

The manipulation arm was controlled in impedance control with novel Time Domain Passivity Control (TDPC). The TDPC allowed safe and transparent operation even with large latencies (between 800-1200ms) and packet loss. The control is based on that presented in Panzirsch *et al.* (2020) and will be presented in a forthcoming work.

A more in-depth evaluation of the hardware and software is given in Krueger *et al.* (2020a).

## 2.3 Experiment setup – ISS

### 2.3.1 Preparing hardware and software for the ISS

Hardware that needs to be sent to the international space station has to undergo a careful qualification campaign and safety approval. This was challenging for the ANALOG-1 hardware due to the high electromechanical complexity of the hardware that had to be uploaded as well as the fact that the experiment involved astronauts and a high-bandwidth ground communication channel. Additional complexity

came from a need to be able to update the software on-board.

There are many requirements and procedures involved in flying a payload on the ISS. These are an integral part of ensuring that the International Space Station can operate as an international collaborative laboratory in a safe and effective manner. The process is guided by the Payload Integration Manager (PIM), and it was no different for ANALOG-1. It is concluded through the issuing of the ‘Certificate of Flight Readiness’ which is the final approval document (“green light”) to proceed with the experiment. However, by being such a complex experiment, ANALOG-1 was faced with a few challenges in order to get the Certificate of Flight Readiness in time for launch. The constructive and effective collaboration with all the parties that steer this process was instrumental to get across the line. This included in particular the safety board, engineering boards, medical boards, software security boards, but also a reactive hardware developer and not least the PIM. This process is given in Krueger *et al.* (2020b).

### 2.3.2 Communication infrastructure

The communication link used between station and ground is principally achieved via the Tracking and Data Relay Satellite System (TDRSS). The interface to this system in the Columbus module of the International Space Station is the Multi-Purpose Communication Computer (MPCC). The MPCC provides an Internet Protocol (IP) based link to the ground node for the payloads, that enabled routing data between the station and the experiment location.

All the communication between entities on the robot and the control station is using Data Distribution Service (DDS). DDS is an advanced publish/subscribe service that is specifically designed for real-time applications in aerospace and defence. The flexibility of DDS enabled the use of it for all the communications required to control the rover; both telemetry, telecommand and video. Even though DDS has its own Transport Layer Security (TLS) the data was sent through a virtual private network (VPN) to ease firewall and routing configurations.

The connection was then also split to different centres on ground. Also here, the security was through the use of VPNs. This way, with the capabilities of DDS, the rover video and telemetry could be seen at the European Astronaut Centre (EAC) and potentially the European Space Operations Centre (ESOC). In addition, the control signals from the space station were routed to the rover in the hangar and could be monitored at all sites.

In addition to those mission specific communication services the standard ISS voice loop system was also used. This system enables voice communication between the different involved operational parties including the astronaut, scientists, EUROCOM and so forth. For this experiment the astronaut was only communicating with the EUROCOM (EAC Operations 2021). The EUROCOM was then coordinating with the geologists and the operations in order to provide the astronaut with support during the sampling operations.

While the European Space Operations Centre in Darmstadt did not have an active role in the ANALOG-1 ISS experiment, it did monitor the telemetry and progress of the experiment in new rover operations tools such as 3DROCS (Joudrier *et al.* 2013) and their software to monitor the mission via the Mission Operations Environment (Cardone *et al.* 2016), installed at EAC.

### 2.3.3 The on-board control station

The on-board control station consisted of a sigma.7 haptic device (Sigma.7 2020), a custom joystick and one of the ISS laptops. The user interface and real-time control ran on this laptop.

The sigma.7 is a commercially available haptic device produced by Force Dimension. It was modified for microgravity use and in order to pass ISS safety and qualification requirements. The astronaut used this device to command motion of the manipulator arm and gripper. Environment forces on the gripper on ground were reproduced by the sigma.7 on orbit, essentially allowing the astronaut to feel what the robotic arm felt.

In addition to the sigma.7, a custom joystick was designed and built by the HRI lab. The joystick served a dual purpose. The first is control of rover elements, like driving, panning with the camera, the selection of operation modes and as confirmation for execution of commands (Figure 4).

The second purpose was to provide an anchor-point for the astronaut to keep a stable body posture in microgravity conditions. For this the joystick has a second, rigid handle with an “enable” button. The sigma.7 was only enabled to command the robot while the button on this handle was pressed. The astronaut would use this handle and the footrest to achieve a stable body posture. If the force-feedback from the sigma.7 became excessive and lead to the astronaut losing grip of the joystick, the “enable” button would be released resulting in a safe state in which no motion could be commanded to the robot.

When it comes to using an onboard laptop on the ISS, the first technical consideration is how to deploy the mis-



**Figure 4.** Astronaut Luca Parmitano operating INTERACT from on-board the ISS

sion specific software. In the case of Analog-1 there were specific requirements for real-time control of the haptic device, the DDS communication and the user interface running directly on the hardware framebuffer. Therefore, the software was a complete custom-built Linux which needed to be installed.

To keep the astronaut time to a minimum in this installation process, the HRI lab developed a bootstrap USB image that could check the onboard computers for uploaded software and install it on the laptop with the only required action from the astronaut being to boot the machine from the USB stick. Once installed, and in coordination with the user centre, subsequent updated images were deployed via the on-board Multi-Purpose Control Computer (MPCC). The deployment image made the technical process to do this very streamlined and easy without needing astronaut time. All updates were still subject to ISS software security approval and configuration control. However, given this simple technical process, and with the help of the security office and software boards, such updates were carried out right up to the experiment start in ANALOG-1. More details on the ANALOG-1 software development are presented in Ferreira *et al.* (2020).

From a technical perspective, it is important to note that the deployment image could be used in the future for uploading software also for other, unrelated, experiments on the station.

The on-board software consisted of the graphical user interface that will be described next as well as the on-board component of the time domain passivity controller. This advanced controller is not only part of the robotic arm but also on the operator side in a bi-lateral control system (Panzirsch *et al.* 2020).

### 2.3.4 User Interface

Besides the mechanical user interfaces (joystick, sigma.7) the main interaction point between the astronaut and the robot is the graphical user interface (GUI) that was running on one of the laptops on-board the International Space Station.

There were considerable constraints on the design of the user interface as it had to run on one of the standard NASA Zbook laptops available on the station. This machine only has a 15" screen, and no touch capabilities. Thus, the GUI was designed to maximise the immersion without having to requalify additional computing hardware. Consequently, the design of the GUI was a trade-off between providing enough, but not too much information to the astronaut on the limited screen size. The visual immersion was maximised by dedicating the majority of the screen real-estate to the video feeds while minimising distracting telemetry and warnings – only showing essential elements such as driving modes, and important warnings when they occurred. The user interface also featured many visual aids that could be enabled or disabled at will by the astronaut, such as a grid to help communication with the scientists during the process of sample selection, and navigation aids showing orientation and speed.

The GUI was built to be as intuitive as possible in order to avoid or minimise the need for prior training. It had detailed built-in help, but also a familiarisation mode in which the astronaut would be able, in a guided step-by-step approach to check out the software, the rover and get used to the controls.

At the end of the experiment a built-in questionnaire captured the astronaut's feedback on his experience.

## 3 Results and discussion

### 3.1 Technical and operational results

During the experiment there were no major technical glitches. The control worked well despite the time delay of almost a second and the astronaut rated his ability to control the rover and perform the tasks highly. As the focus of ANALOG-1 ISS was largely to represent with high fidelity the challenges of controlling a robotic asset on a planetary surface from an astronaut on-board a spacecraft, the experiment must be declared very successful with respect to the objectives that were addressed.

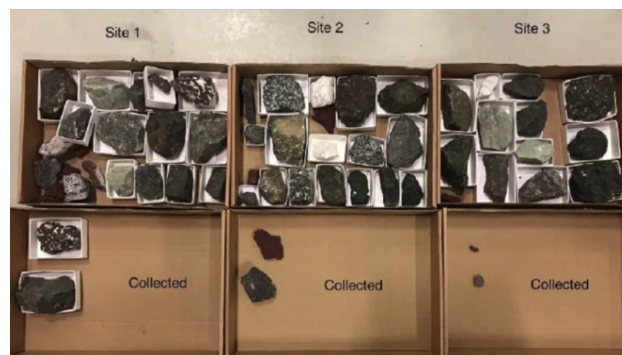
Despite this, there were elements of the user interface the astronaut did not make a lot of use of, such as for exam-

ple the chat window, or the ability to move the navigation camera. As described in this paper, the attempt was made to make an immersive control station and a very versatile avatar, and these answers from the astronaut are an indication that the astronaut was not able to make full use of the tools provided to him, the reason possibly being operational rather than technical. This was evidenced by the fact that he waited for the ground support to guide his moves (as is common practice in astronaut operations) instead of physically moving the rover around and exploring the site with the arm himself.

It will be important to see if and how these factors change during the ANALOG-1 ground campaign in 2022, when the network infrastructure and the complexity of astronaut operations are significantly reduced. The opportunity should be taken to devise an operational scenario that makes more use of this immersive avatar and the ability for continuous direct communication with a backroom, and then compare and contrast the performance achievable in order to also inform future decisions for how to make best use of astronauts to control robotic assets.

The limitations of the artificial setting did not have a significant impact on the operational scenario, which was successfully completed in all its steps (general overview, sample selection and sampling procedure) and within the foreseen timeframe, nor did the effectiveness of the communication with the scientists suffer any drawbacks. Hence, from the operational point of view, the applicability of the indoor analogue scenario was acceptable, but with room for improvement. Some aspects that would help make the scenario more realistic include using more realistic outcrop material, integrating a higher variation in textures, and shaping a more uneven terrain. In particular, the trafficability aspect was oversimplified given that the track was already well defined on flat smooth concrete with the complete absence of any significant obstacles. As ANALOG-1 is an operational experiment, the major intent was to replicate as closely as possible operational aspects of the EL3 sample return mission with particular emphasis on the procedures and decision making process. As such more realism in the environment is better in that it creates a better scenario immersion, but not necessary to meet the objectives. The major difference between carrying out the experiment indoors and in an outdoor setting such as Mount Etna or Lanzarote is associated with the environmental conditions, e.g., lighting, surface texture, traversing distance.

The scientific outcome of the operations was limited more due to the artificial and simplified set up. Particularly critical was the uneven artificial lighting throughout the whole hangar. This resulted in significant issues with the dynamic exposure compensation of the camera, and over



**Figure 5.** The rock samples used in ANALOG-1

saturated images during the sample selection. However, since on the Moon such variable light is also to be expected, it is important that dedicated simulations and tests are done prior to launch to find the best solution for dealing with the variability.

This applies also to the white point and colour balance of the camera, which needs to be calibrated in accordance to the environmental light source spectrum.

The resolution of the cameras did not allow a detailed distinction among different rocks, minerals and textures which were frequently barely visible during sample collection, except for when the gripper camera got extremely close. This affected the decisional process of the samples to be collected and may have had a knock-on effect on the operations, as the information received by the science team was lacking.

However, some of these conclusions were probably also affected by an overly traditional approach to the operations, in which the scientists had to take the time to discuss which rock to sample and then, through EUROCOM, communicate this to the astronaut. It may have been better, and more in line with the available immersive and versatile robotic avatar, for the astronaut to be given more autonomy to drive around and make use of the immersive telepresence and his geology training to pick up various rocks for close inspection, discarding rocks that were not interesting in constant and direct dialogue with the supporting science team on ground. Additionally, the astronaut had not been trained on the terrain. This presented extra difficulties, but also representativeness with respect to a real operational scenario.

## 3.2 Important lessons

### Visual experience

In order to drive a rover to select rocks and for situation awareness visual cues are important and need to be tailored



to the purpose and to the user. During ANALOG-1 the video streams were delivered in fixed resolution and framerate, allowing the optimisation of compression and bandwidth while maintaining a smooth driving experience. However, it became clear that in other situations, like during rock investigation, the resolution, white balance and colour range were more important drivers. Thus, future systems could offer different settings that can be selected by the astronaut based on the operation that is being performed.

#### **Maximise full training and awareness of system capabilities to the whole operations team**

The astronaut and operators have to daily interface with many systems from different experiments and it is only human to forget some of it. Also, astronaut operations follow very strict protocols which automatically placed limits on which features of the ANALOG-1 system could be used. On the other side it is unfortunate for the system capabilities not to be fully utilised or for a feature being requested in the debrief that was, in fact, available. More refresher training, tutorials and hints in the interface would probably help bridge the gap to full utilisation.

#### **Direct communication between specialists and the astronaut**

On the space station any misunderstanding can lead to hazards and are therefore handled through strict procedures with communication through a single interface person; the EUROCOM. However, in this closed remote experiment environment, direct interaction between the geologists and the astronaut would clearly have increased operation speed and efficiency, allowing the astronaut to leverage his excellent grasp of the remote system as well as his geology training.

### **3.3 The ANALOG-1 complete ground test campaign**

The operational objectives related to ground operations with supervised autonomy were not addressed by ANALOG-1 ISS but will be a primary objective of the forthcoming ground campaign. In this next part of ANALOG-1, ESOC will feature as the main operations centre when these important objectives, developed through previous METERON experiments such as SUPVIS-M (Taubert *et al.* 2017), are fully integrated with the ANALOG-1 scenario and executed as a part of DLR's ARCHES space demo-mission. This is planned to take place on Mount Etna in the summer of 2022.

During the ground campaign the high-fidelity Gateway analogue used in ANALOG-1 ISS (i.e. the International Space Station) is replaced with a simple analogue (e.g. a room in a hotel and a simple network). Meanwhile the terrain analogue will increase in complexity. Thus it will be possible, ANALOG-1 being an operational experiment, to assess the sensitivity to the inclusion of the ISS on the operational procedures over a ground scenario where the implementation of the procedures is much more straightforward.

## **4 Conclusions**

Technically the ANALOG-1 ISS experiment was successful in that the astronaut was able to effectively and efficiently make use of his robotic avatar and complete the task in a very short time. Specifically, he had to navigate approximately 150 meters, find the three sampling sites, investigate them in terms of geology, and explore the rocks he found and finally collect two samples from each. This was done in constant coordination and contact with the Operations centre at EAC and the science backroom, also at EAC. All of this was achieved in 70 minutes despite the astronaut not having any prior training on the terrain. This impressive performance was also reflected by Luca's answers to the questionnaire. Luca scored particularly highly the ease of access of relevant information on screen, his ability to concentrate on the task, and the level of proficiency with the robotic avatar that he was able to achieve. He also rated highly the usefulness and sufficiency of his geology training.

Scientifically, the operational process had some room for improvement, particularly in the way the geologically significant samples were identified, though this was also to be expected given the simplified indoor setup. The 2022 ground test campaign will focus on having a more representative ground analogue and realistic operational scenario.

#### **Re-use of ANALOG-1 hardware**

The sigma.7 and joystick as well as the mounts are still, as of the time of writing this paper, on board the station, and anyone who wishes to reuse it are invited to contact the authors. At the time of writing of this paper, the ANALOG-1 ISS hardware is being used by CNES' Pilotes experiment (Pilotes 2021), and will also be used in the upcoming Surface Avatar experiment to control a fleet of heterogenous robots.

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