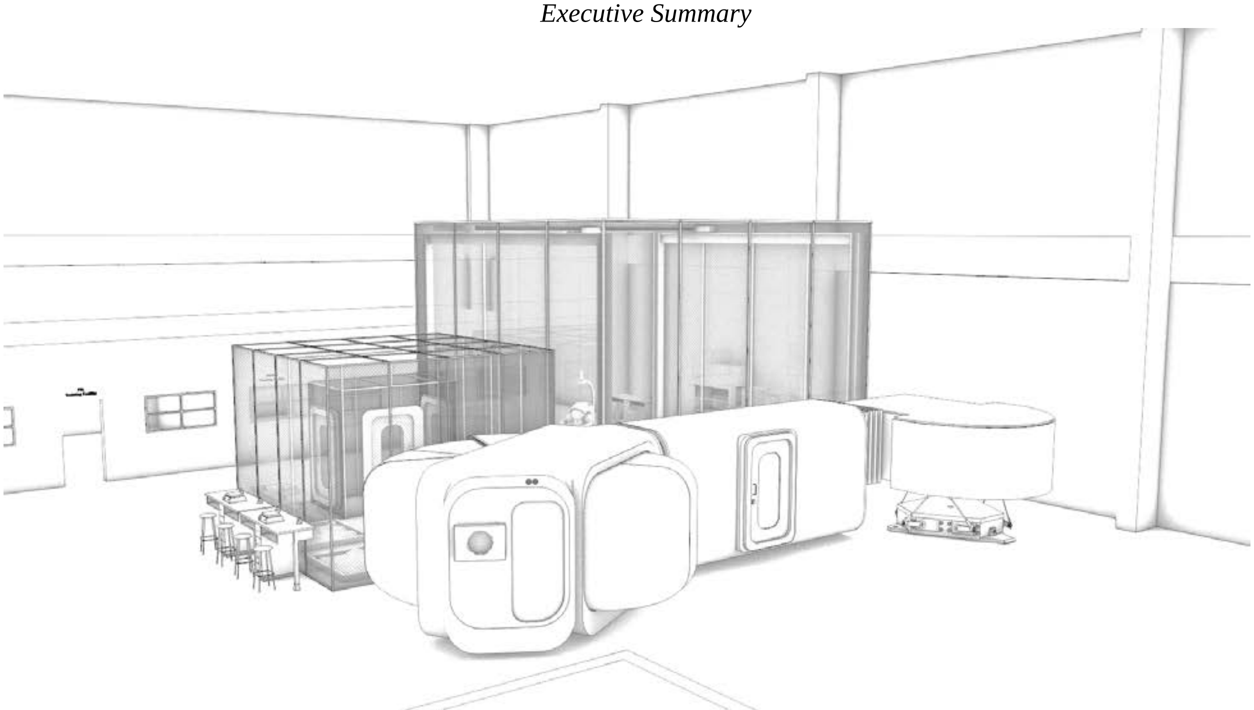
ANALOGUES FOR PREPARING ROBOTIC AND HUMAN EXPLORATION ON THE MOON

ESA GSP Study, Contract 4000111890

Executive Summary



Prepared by: Tom Hoppenbrouwers, Diego Urbina, Space Applications Services, Belgium
Accepted by: Andreas Diekmann, ESA

ABSTRACT

In view of lunar exploration, which is foreseen to be one of the next steps in human space exploration, Lunar Analogues are and will continue to be **powerful tools to support the development, demonstration and validation of new technologies and operational concepts.** Furthermore Lunar Analogues will serve as an environment for Astronaut training, Behavioural Health and Performance research as well as providing engaging activities for the public.

There is in particular a **growing interest in Artificial Lunar Analogues**, which offer a wider range of simulation capacity than Natural Analogues and also provide a more controlled and standardized environment and thus facilitate the comparison between different simulation campaigns. Artificial Lunar Analogues also offer the benefit of reduced preparation overhead and logistics cost, with respect to simulation campaigns in Natural Analogues.

Under ESA's General Studies Programme (GSP) a Consortium consisting of Space Applications Services NV/SA, LIQUIFER Systems Group and COMEX SA has performed the **Lunar Analogues (LUNA) study, with the objective to identify missing Artificial Lunar Analogues, taking into account the demands for such analogues and considering existing and planned analogues, and to establish technical, utilisation and implementation concepts for the most needed analogues.**

This executive summary describes the approach and results of the study, from identifying more than 150 Needs addressable by Artificial Lunar Analogues (needs identified through Roadmap analysis, literature review and consultation of more than 100 Subject Matter Experts in a broad variety of fields worldwide), over establishing a Catalogue of already existing or planned Artificial Analogues, to performing a **gap analysis identifying which identified Needs are not met by existing or planned Analogues.** Based on this gap analysis the Consortium proposed three different Artificial Lunar Analogue concepts to ESA in order to complement existing or build up new facilities that might be a future contribution to the international effort of exploring the Moon. Finally **ESA selected one of the concepts to be further detailed in terms of technical characteristics, utilisation scenarios and implementation aspects.** This concept is called **'European Surface Operations Laboratory' or 'ESOL'** and is proposed to be implemented at the EAC/DLR site in Cologne, Germany.

I. INTRODUCTION

I.I Definitions

Lunar Analogues can be roughly divided in three groups: Natural, Artificial and Mixed Lunar Analogues.

Natural Lunar Analogues are terrestrial analogue environments like deserts, craters or other surfaces on Earth which are representative for terrain, soil, etc. of the Moon.

***Artificial Lunar Analogues* are human-made terrestrial facilities and/or tools that provide conditions that are analogue to specific conditions on the Moon or to conditions in human-made environments on the Moon (e.g. a lunar lander or habitat), and that can be used to simulate and train lunar exploration missions.** Artificial Lunar Analogues can be physical, virtual or a combination of both.

Mixed Lunar Analogues are human-made terrestrial facilities that are placed in a natural analogue environment. Examples are the Aquarius underwater habitat used in the frame of the NASA Extreme Environment Mission Operations (NEEMO) program or the Deep Space Habitat used in the frame of the NASA Desert RATS (Research and Technology Studies) campaigns.

I.II Study background

In view of lunar exploration, which is foreseen to be one of the next steps in human space exploration, lunar analogues are and will continue to be powerful tools to support the development, demonstration and validation of new technologies and operational concepts. Furthermore lunar analogues will serve as training environment for astronauts and will engage the public with interesting and exciting mission simulations well before actual missions take place.

Natural Lunar Analogues have the advantage that they simulate certain aspects of the lunar environment “for free”, i.e. terrain, soil and harsh environment (dust, temperature, psychological effects, etc.). However there are limitations in their simulation capacity and also logistics disadvantages as Natural Analogues are often in remote locations and the deployment of people and equipment is then complicated and costly.

Therefore, there is a **growing interest in Artificial Lunar Analogues in order to avoid the disadvantages of the Natural Lunar Analogues. The main benefits of working with Artificial Lunar Analogues are**[1]:

- Ability to **control the inside/outside environment** (e.g. ‘inside’ for a lunar habitat or ‘outside’ for a rover testbed).
- **Standardization** of the analogue and tests in order to allow a meaningful comparison between several simulation campaigns. The reduction of noise factors, like weather or climate at the Natural Analogue site, result in improved test quality.
- **Features that are not available in Natural Analogues** such as gravity offloading devices, habitats, or high-fidelity (even icy) regolith.
- Significantly **reduced logistical preparations and costs** compared to simulation campaigns in Natural Analogues.
- Increased (net) test-time compared to Natural and Mixed Analogues, because reduced logistics (easier access) and independence from weather noise factors (an Artificial Analogue is weather-independent) allow more test runs within a given campaign period.
- Easier access and lower cost stimulate **earlier integrated operations simulation campaigns** with different hardware and test communities. This leads to an increased knowledge transfer amongst all involved partners and to more robust hardware and better mission operations concepts.
- Easier access and higher attraction for the general public, thus **higher outreach potential** compared to Natural Analogues.

Under ESA’s General Studies Programme (GSP) a Consortium consisting of Space Applications Services NV/SA (prime), LIQUIFER Systems Group and COMEX SA has performed the Lunar Analogues (LUNA) study[*]. **The objective of this ESA study is to identify the needs for Artificial Lunar Analogues, to analyse whether existing and planned Artificial Lunar Analogues in Europe and worldwide are sufficient to meet those needs, or whether there are gaps in analogue capacity, and to conceive new Artificial Lunar Analogues as a response to the identified gaps.**

Natural Lunar Analogues are not considered in this study (as they were already addressed in the CAFE study[2]). Furthermore, the study focuses on ‘Robotic and Human Exploration on the Moon’, i.e. lunar surface operations. Therefore lunar analogue needs related to proximity, landing and rendez-vous & docking operations are not considered.

[*] ESA GSP study, carried out by a consortium led by Space Applications Services NV/SA under contract No. 4000111890.

II. NEEDS ANALYSIS

II.I Needs identification and classification

A **Needs Database was drawn** from the NASA Space Technologies Roadmap[3], ESA Exploration Technology Roadmap[4], ESA Lunar Design Reference Mission (DRM)[5] and ISEGC (International Space Exploration Coordination Group) Global Exploration Roadmap[6], followed by reviewing and parsing relevant technical papers from various journals and conferences.

For Human Research purposes, the study team relied particularly on the NASA Analogue Assessment Tool Report (AATR)[7]. The AATR was created under the aegis of the NASA Human Research Program. It comprises a list of desirable characteristics of Analogues identified by psychologist and human behaviour scientists for Behavioural Health and Performance (BHP) research in order to achieve comparability to long duration human spaceflight missions.

An additional source of inputs for the Needs Database were 106 Subject Matter Experts (SMEs) (out of 276 SMEs that were addressed) from all over the world and from all relevant disciplines. The SMEs responded to a questionnaire that was aimed at soliciting SME views on what is relevant / required / of interest to them in the context of Artificial Lunar Analogues.

Ten of these SMEs have been consulted throughout the subsequent phases of the Lunar Analogues study for further in depth interviews and overall advice with respect to the proposed Artificial Analogue concepts.

In total, the whole process of needs identification resulted in 159 individual Needs identified.

These 159 Needs were than ranked according to their prominence in the roadmaps, reference missions and publications, and with respect to their importance for the SMEs. 19 Needs came out with a high significance rating. These Needs are called the **'driving Needs'** and can be categorized in 6 main groups:

1. Testing In-Situ Resource Utilization (ISRU) mining, extracting, constructing processes;
2. Studying the impact of communication constraints (bandwidth, delay) on tele-operations and robotics deployment;
3. Dust prevention and mitigation;
4. Verification and Validation of systems, procedures and new operational concepts;
5. Partial gravity evaluation of Extra Vehicular Activity (EVA) tasks and tools handling;
6. Testing (semi-)closed loop Environmental Control and Life Support Systems (ECLSS).

For more details see the infographic on the next page.

II.II Technical Features (TFs) and Fidelity Characteristics (FCs)

To each of the identified Needs key specifications of an Analogue that would meet/address this Need (irrespective of whether such Analogue exists or not) are attributed. These key specifications are called Technical Features (TFs) and Fidelity Characteristics (FCs). Technical Features (TFs) are physical features that can be included in an Analogue (e.g. a regolith testbed, a control room, communications set-up for delayed communications). Fidelity Characteristics (FCs) concern BHP research and describe the fidelity of simulation campaigns for satisfying BHP Needs (e.g. crew autonomy or physical isolation). They were identified based on the AATR[3]. TFs and FCs were used by the study team in order to determine how well each identified Need can be addressed. A certain Need can only be fully addressed by a certain Artificial Analogue, when the Analogue has the right combination of Technical Features and Fidelity Characteristics, i.e. a combination that corresponds to the TFs and FCs of the respective need.

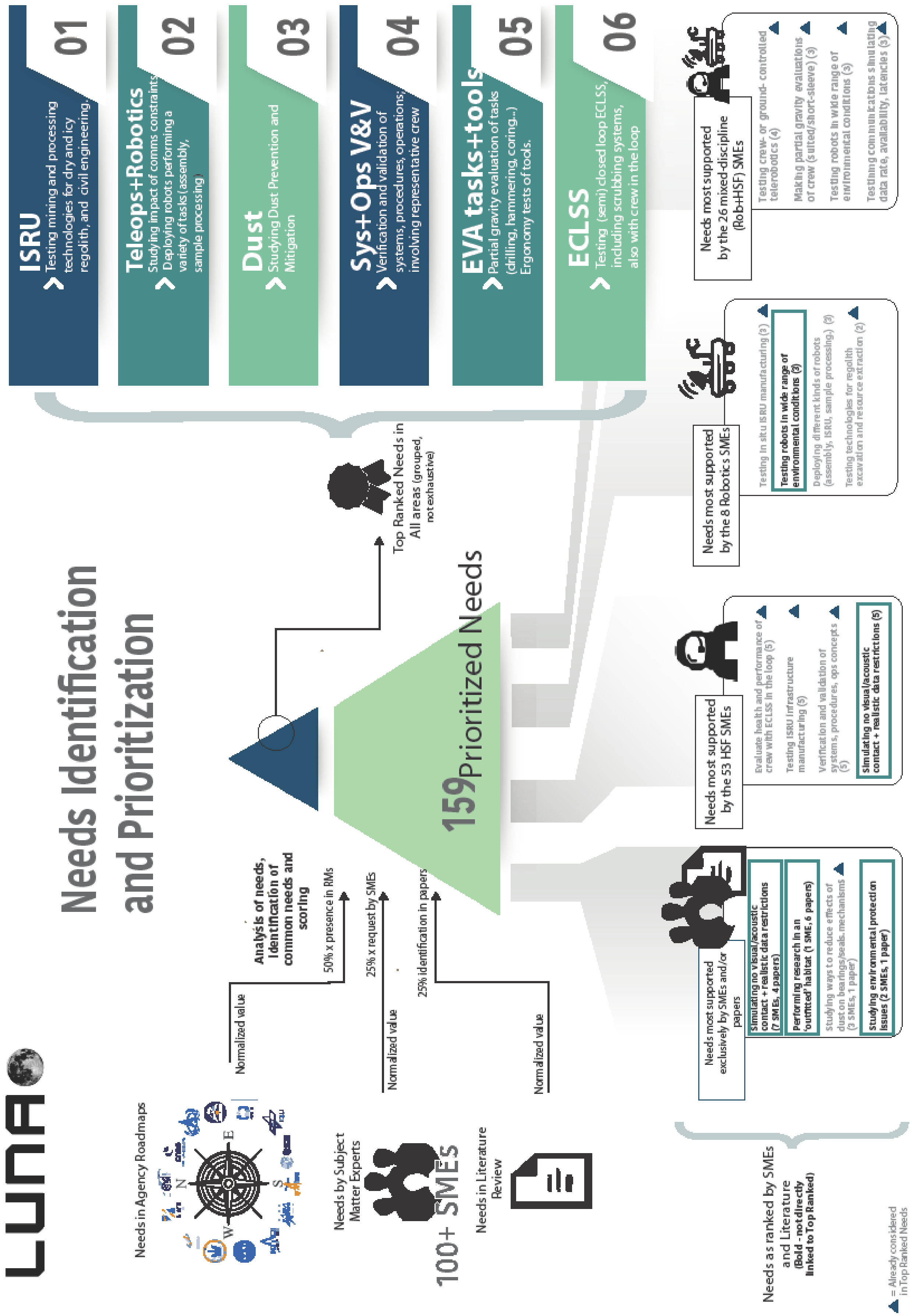
III. CATALOGUE OF EXISTING ARTIFICIAL ANALOGUES

III.I Scope of the Artificial Analogues catalogue

In parallel with the establishment of the Needs Database **a catalogue of existing Artificial Analogues that can be utilized for mission simulation and preparation of future lunar missions has been developed.** This catalogue is not limited to facilities in ESA Member States, but gives an overview on facilities available worldwide.

The Artificial Analogues catalogue is complementary to the past ESA study "Concepts for Activities in the Field for Exploration (CAFE)[2]" that provides a survey of Natural Analogues. It can also be seen as complementary to the ongoing effort by the International Human Space Flight Analog Research Coordination Group (HANA) to set up a catalogue of Ground-based Flight Analogues whose scope is only Human Space Flight, which does not make distinctions between Natural and Artificial Analogues, and which targets long duration space flight (does not necessarily focus on the Moon).

In order to limit the range of the study, a separation was drawn between "Artificial Analogues" and "Testbeds". Artificial Analogues are facilities that allow simulation of a range of specific aspects of space missions within a controlled environment. Testbeds (or Test Facilities) on the other hand allow to simulate and test only one specific aspect of a space condition (e.g. in a thermal vacuum chamber), but they do not allow to simulate a whole mission scenario (e.g. field exploration with a robot or astronaut). Testbeds are not included in the Artificial Analogues catalogue.


LUNA
Needs Identification and Prioritization
Needs in Agency Roadmaps
Needs by Subject Matter Experts
100+ SMEs
Needs in Literature Review
Normalized value
Normalized value
Normalized value
50% x presence in RMs
25% x request by SMEs
25% identification in papers
Analysis of needs, identification of common needs and scoring
159 Prioritized Needs
Top Ranked Needs in All areas (grouped, not exhaustive)
01 ISRU
Testing mining and processing technologies for dry and icy regolith, and civil engineering.
02 Teleops+Robotics
Studying impact of comms constraints
Deploying robots performing a variety of tasks (assembly, sample processing)
03 Dust
Studying Dust Prevention and Mitigation
04 Sys+Ops V&V
Verification and validation of systems, procedures, operations; involving representative crew
05 EVA tasks+tools
Partial gravity evaluation of tasks (drilling, hammering, coring..)
Ergonomy tests of tools.
06 ECLSS
Testing (semi) closed loop ECLSS, including scrubbing systems, also with crew in the loop
Needs as ranked by SMEs and Literature
(Bold - not directly linked to Top Ranked)
Needs most supported exclusively by SMEs and/or papers
Simulating no visual/acoustic contact + realistic data restrictions (7 SMEs, 4 papers)
Performing research in an "outfitted" habitat (1 SME, 6 papers)
Studying ways to reduce effects of dust on bearings/seals, mechanisms (3 SMEs, 1 paper)
Studying environmental protection issues (2 SMEs, 1 paper)
Needs most supported by the 53 HSF SMEs
Evaluate health and performance of crew with ECLSS in the loop (5)
Testing ISRU infrastructure manufacturing (5)
Verification and validation of systems, procedures, ops concepts (5)
Simulating no visual/acoustic contact + realistic data restrictions (5)
Needs most supported by the 8 Robotics SMEs
Testing in situ ISRU manufacturing (3)
Testing robots in wide range of environmental conditions (3)
Deploying different kinds of robots (assembly, ISRU, sample processing) (3)
Testing technologies for regolith excavation and resource extraction (2)
Needs most supported by the 26 mixed-discipline (Rob+HSF) SMEs
Testing crew- or ground-controlled telerobotics (4)
Making partial gravity evaluations of crew (suited/short-sleeve) (3)
Testing robots in wide range of environmental conditions (3)
Testing communications simulating data rate, availability, latencies (3)
= Already considered in Top Ranked Needs

III.II Artificial Analogues catalogue in a nutshell

The research performed as part of this study led to the identification of 47 facilities in the world, with a high number of facilities located in Europe and the US. The list is not exhaustive; additional facilities exist e.g. in China, Russia and India, but the available data on those are sparse.

The survey and geographic mapping of facilities showed that in Europe exists a cluster of various facilities in Cologne and in Torino. The DLR site (German Aerospace Center) in Cologne offers the possibility to combine several facilities, e.g. the European Astronaut Centre (EAC) and the :envihab, DLR for complex mission simulations; the TAS-I and ALTEC facilities can do so in Torino. A similar situation can be stated for the US at NASA's Johnson Space Center (JSC). In the Artificial Analogues catalogue each facility has been characterized by its Technical Features and Fidelity Characteristics, which were already introduced for the establishment of the Needs Database (see chapter II.II).

IV. GAP ANALYSIS

IV.I Needs vs. Analogues mapping matrix

The methodology used for identifying the gaps in current Artificial Analogue infrastructure is based on attributing Technical Features (TFs) and Fidelity Characteristics (FCs) to the identified Needs and the characterization of the existing Artificial Analogues by exactly the same TFs and FCs. Theoretically, a facility that possesses/matches all the TFs and FCs of a Need, completely satisfies that Need. Reality, however, is more complex, and whether a facility will perfectly satisfy a need will depend on the specifics of the individual TFs and FCs, on the characteristics of the very tests to be performed, and many other factors.

Nevertheless, linking the individual Needs and the available Analogues, using the TFs and FCs as a bridge, effectively connects the results of the Needs Identification and the list of available Analogues, providing valuable information to what extent the Needs are fulfilled by the existing Analogue infrastructure and what Needs may be lacking infrastructure to support them. And, while being a simplified representation of the complexities of the large picture, it will be a powerful tool to be used for the 'gap analysis'. **A 'Needs vs. Analogues mapping matrix' has been established, as presented in Figure 1. This matrix contains the percentage of TFs or FCs that each facility satisfies, per Need. Finally, this allows to identify the gaps in the existing Analogue infrastructure.**

IV.II Gap Analysis results

Following the Needs significance rating and subsequent analysis, which confirmed that the 19 'driving Needs' provide a good coverage of the different groups of Needs, the gap analysis has been performed on these 'driving Needs'. The following gaps have been identified (see also the infographic on page 7):

Facilities allowing to perform regolith excavation, material transfer, handling, and processing – both with rovers and astronaut EVA tools – are currently not available in Europe. There is a special interest (also worldwide) in facilities to test **water-volatile extraction and separation from lunar polar icy material**. Furthermore various European science and engineering communities would benefit from the availability of medium/large amount of physical fidelity lunar simulant in combination with an area which can be used for **3D printing/constructing with the lunar regolith simulant.**

Worldwide there is a gap in facilities allowing to study the impact of dust in various system interfaces. Habitat/vehicle egress/ingress facilities need to be available, operating in a context involving regolith simulant, also electrostatically charged. Furthermore, the habitat should allow **(semi-)closed loop ECLSS research and demonstration**, e.g. for the European MELISSA, and BHP related research.

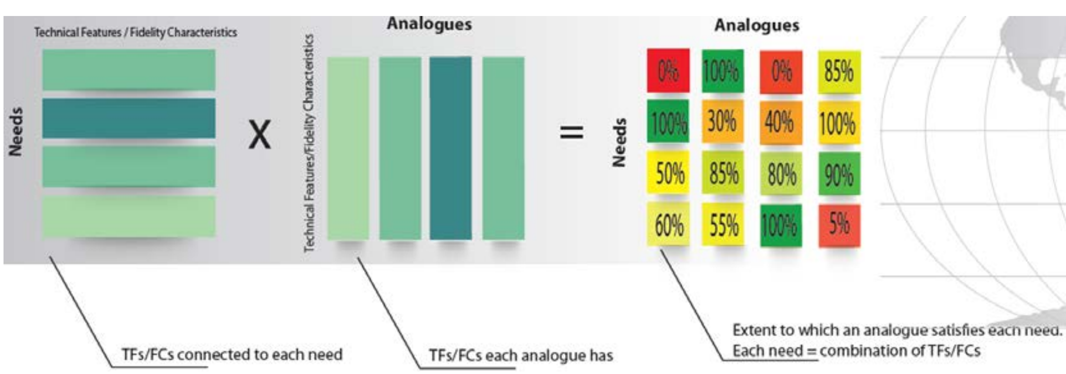


Figure 1 Gap Analysis methodology: creation of the 'Needs vs. Analogues mapping matrix'

Exploration roadmaps highlight the importance of **testing advanced human-robot cooperation strategies**. A permanent analogue facility that supports this kind of tests would be a valuable asset. The thriving field of space teleoperations in Europe would gain from having access to a setup allowing for robotic control, with AOS/LOS, bandwidth throttling, and communication delay, in combination with Lunar terrain features and soil simulant.

Active response robotic off-loading for crew in pressurized suits is missing worldwide, for short sleeve it exists in the US, but it is missing in Europe. Integrating active response robotic off-loading into an artificial Lunar Analogue would benefit from the **combination with a regolith simulant testbed**; this combination of Technical Features is a worldwide gap, too.

Analogue facilities suited for high-level integrated simulations, combining a habitat, lunar terrain, a Mission Control Centre (MCC), related communications simulations, relevant environmental characteristics, and software allowing for system level simulations are not easily available to European researchers and operations developers.

V. ARTIFICIAL LUNAR ANALOGUE CONCEPTS

The gap analysis performed resulted in the identification of gaps (see section IV.II and the infographic on the next page), but it also gave an indication which existing Analogue Facilities in Europe already have a good potential (i.e. address several Needs of the user community) and thus constitute 'prime locations' for evolving towards a more complete Artificial Lunar Analogue Facility. The study considers the following three prime locations as particularly interesting for establishing an Artificial Lunar Analogue:

- The Hydrosphere facility in Marseille, France.
- The ALTEC/TAS-I facilities in Torino, Italy.
- The EAC/DLR site in Cologne, Germany.

For each of these prime locations, the study developed a broad concept for an Artificial Lunar Analogue.

V.I Hydrosphere Artificial Analogue Concept

The Hydrosphere is an ESA Ground Based Facility, located in Marseilles, France. Initially it was built and used as diving simulator for training of offshore divers to 450bars. It is part of the COMEX CEH complex, which was used in the past by the European Space Agency and CNES (French Space Agency) for confinement tests with divers. Such tests included psychological assessment in confinement conditions (hermetically closed), telemedicine, but also biological contamination research and life support system testing.

The habitat section of Hydrosphere has a volume close to the volume of ESA's Columbus laboratory at the ISS. It can be used to test life-support systems (in closed or semi-closed loop). The installation includes a 5m diameter sphere, which can be used for EVA training in medium vacuum or for human and robotic sampling techniques. COMEX has two EVA suit mock-ups available at the Hydrosphere facility.

The following modifications are proposed to be implemented at the Hydrosphere complex in order to perform lunar mission simulations: greenhouse (food growth facility), lunar terrain morphology with a regolith simulant testbed in the sphere (medium vacuum class), and an intermediate chamber between the habitat and the EVA sphere which can be equipped as airlock allowing therefore the simulation of dust-related problems and validation of technical solutions (e.g. air filtration or suit port architecture).

This Artificial Analogue offers the possibility to simulate complex scenarios of lunar exploration with EVA or robotic interventions on a soil simulant in medium vacuum including a hermetically closed habitat with access port to the EVA sphere.

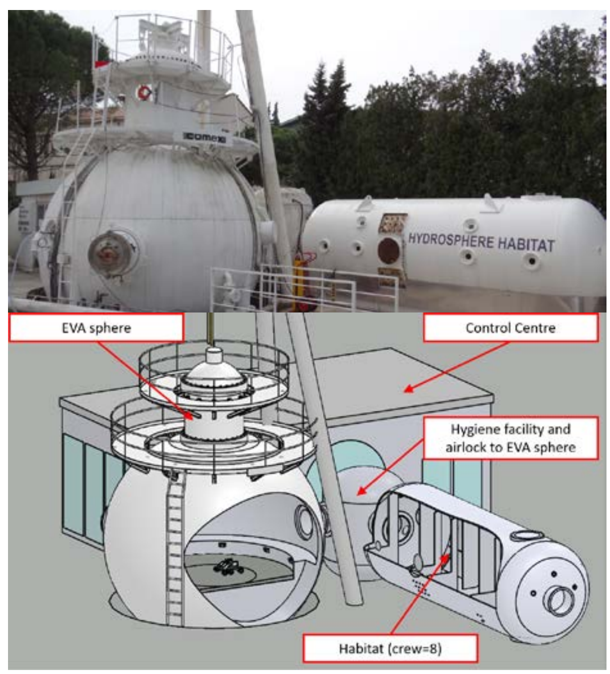
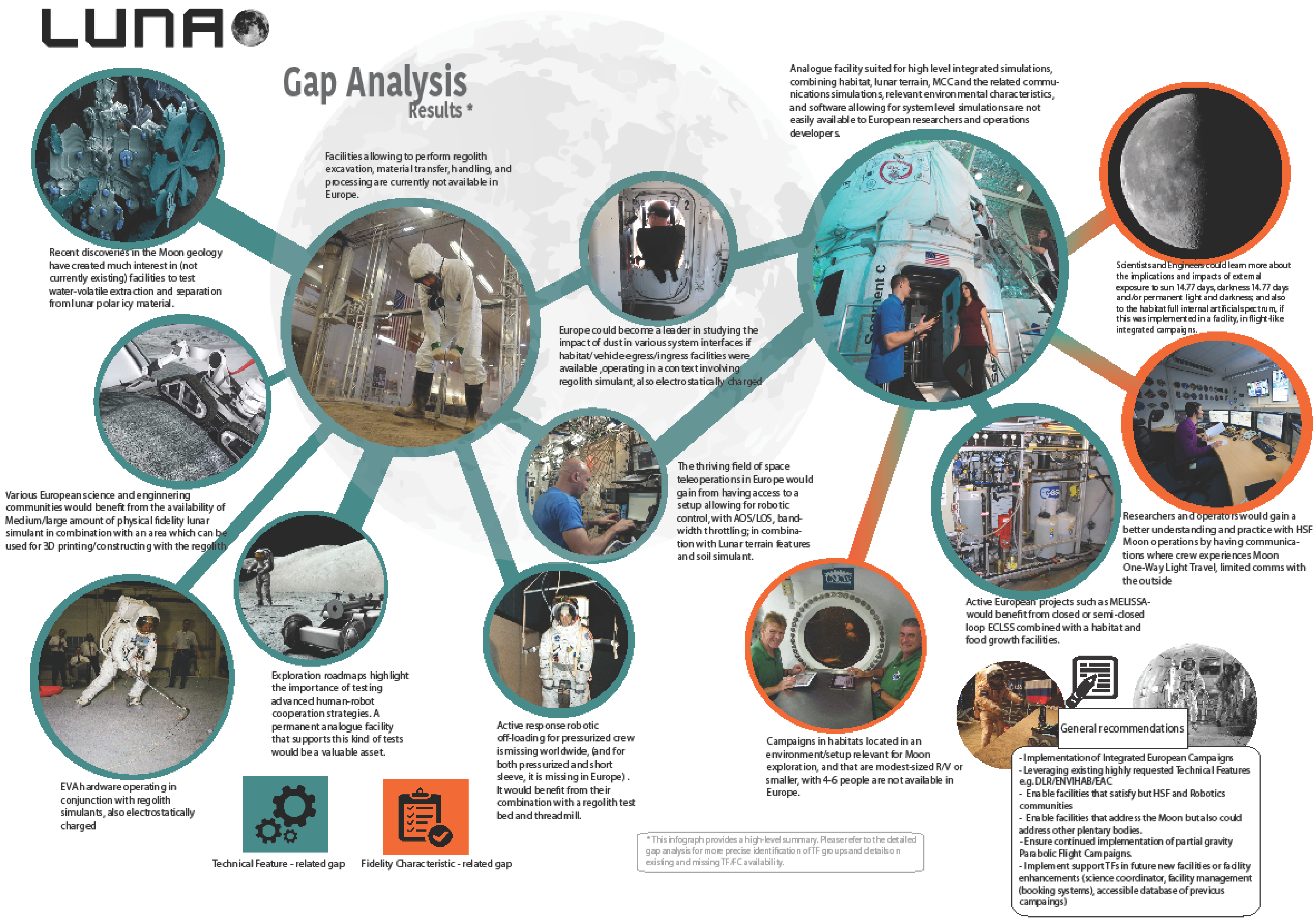


Figure 2 Hydrosphere artificial analogue concept


LUNA
Gap Analysis
Results *
Recent discoveries in the Moon geology have created much interest in (not currently existing) facilities to test water-volatile extraction and separation from lunar polar icy material.
Facilities allowing to perform regolith excavation, material transfer, handling, and processing are currently not available in Europe.
Various European science and enginnering communities would benefit from the availability of Medium/large amount of physical fidelity lunar simulant in combination with an area which can be used for 3D printing/constructing with the regolith
Europe could become a leader in studying the impact of dust in various system interfaces if habitat/ vehicle egress/ingress facilities were available ,operating in a context involving regolith simulant, also electrostatically charged
Analogue facility suited for high level integrated simulations, combining habitat, lunar terrain, MCC and the related communications simulations, relevant environmental characteristics, and software allowing for system level simulations are not easily available to European researchers and operations developers.
Scientists and Engineers could learn more about the implications and impacts of external exposure to sun 14.77 days, darkness 14.77 days and/or permanent light and darkness; and also to the habitat full internal artificial spectrum, if this was implemented in a facility, in flight-like integrated campaigns.
The thriving field of space teleoperations in Europe would gain from having access to a setup allowing for robotic control, with AOS/LOS, band-width throttling; in combination with Lunar terrain features and soil simulant.
Researchers and operators would gain a better understanding and practice with HSF Moon operations by having communications where crew experiences Moon One-Way Light Travel, limited comms with the outside
Active European projects such as MELISSA- would benefit from closed or semi-closed loop ECLSS combined with a habitat and food growth facilities.
EVA hardware operating in conjunction with regolith simulants, also electrostatically charged
Exploration roadmaps highlight the importance of testing advanced human-robot cooperation strategies. A permanent analogue facility that supports this kind of tests would be a valuable asset.
Active response robotic off-loading for pressurized crew is missing worldwide, (and for both pressurized and short sleeve, it is missing in Europe) . It would benefit from their combination with a regolith test bed and threadmill.
Campaigns in habitats located in an environment/setup relevant for Moon exploration, and that are modest-sized R/V or smaller, with 4-6 people are not available in Europe.
General recommendations
- Implementation of Integrated European Campaigns
- Leveraging existing highly requested Technical Features e.g. DLR/ENVIHAB/EAC
- Enable facilities that satisfy but HSF and Robotics communities
- Enable facilities that address the Moon but also could address other plentary bodies.
- Ensure continued implementation of partial gravity Parabolic Flight Campaigns
- Implement support TFs in future new facilities or facility enhancements (science coordinator, facility management (booking systems), accessible database of previous campaings)
Technical Feature - related gap
Fidelity Characteristic - related gap
* This infograph provides a high-level summary. Please refer to the detailed gap analysis for more precise identification of TF groups and details on existing and missing TF/FC availability.

V.II GRAN Torino Analogue Concept

The Thales Alenia Space Italy - ALTEC premises in Torino, contains several existing analogue facilities established as part of the HRE STEPS programme (Human and Robotics Exploration, Sistemi e Tecnologie per l'EsPlorazione Spaziale), which makes it a good base to implement an Artificial Lunar Analogue facility, titled GRAN Torino – GRound based ANalogue Torino.

The existing infrastructure offers the following: Neutral Buoyancy Test Facility (NBTF), Mars and Moon Terrain Demonstrator (MMTD) currently outfitted with Martian soil simulant, outdoor rover testbed (~600sqm) outfitted for Mars simulations, technical areas where temperature, humidity, air and environment cleanliness are controlled and kept within predefined limits (Green Rooms and Clean Rooms), classrooms and spaces for training and dissemination of scientific and technological space activities, Virtual Reality Lab and Collaboration Room, Technological Engineering areas (thermal control, etc.) and Rendez-Vous & Docking facility to simulate RV&D of surface elements.

The following components are proposed to be implemented at Thales Alenia Space Italy - ALTEC in order to perform lunar mission simulations: modification of the Mars & Moon Terrain Demonstrator to make it suitable for lunar mission simulations, a habitat sized for two to four crew-members for simulations of maximum two weeks, two EVA suit mock-ups, EVA and MCC information system, Mission Control Centre (MCC), system level simulator, gravity off-loading device, and a widely compatible robot control station.

Figure 3 Mars Moon Terrain Demonstrator (MMTD) [Image courtesy ALTEC S.p.A.]

V.III EAC/DLR Artificial Analogue Concept

The DLR site in Cologne, Germany, contains several existing analogue facilities – facilities at :envihab and at the European Astronaut Centre (EAC) – which makes it a good base to implement an Artificial Lunar Analogue facility.

The EAC facilities already include the **Neutral Buoyancy Facility (NBF), Classroom and Auditorium infrastructure, a Mission Control / Simulation Control Centre set-up and the big Training Hall** in which a large area can be dedicated to new components of the Artificial Analogue. Besides the above mentioned on-site facilities, **EAC contains a very specific and valuable human capital: directly relevant expertise and know-how from the astronauts, astronaut instructors, flight surgeons and astronaut medical support team, and education & outreach people.**

The following components are proposed to be implemented in the EAC Training Hall in order to perform lunar mission simulations: **regolith simulant testbed**, **habitat** sized for two to four crew-members for simulations of max. two weeks (the SHEE habitat – Self Deployable Habitat for Extreme Environments), **two EVA suit mock-ups** (usable in dry environment, like in the regolith simulant testbed, but also in water immersion partial gravity, like in the NBF), a **gravity off-loading system** (for humans, compatible with the EVA suit mock-ups, and for rovers), a **system level simulator, full motion simulator** (6 degree of freedom lunar rover simulator with a virtual reality rendering of the lunar surface), a **Mission Control Centre (MCC),** an **EVA and MCC information system** (chest and wrist displays for the EVA suit and system allowing to introduce communication delays, bandwidth throttling, etc.), a **widely compatible robot control station**, and a **food growth facility.** Furthermore, a **~1000sqm rover testbed**, featuring lunar terrain morphology, is proposed to be built in a new greenhouse-type building next to the EAC building. This big testbed would also be valuable for the purpose of testing 3D-printing of larger structures by means of solar sintering of lunar regolith simulant or other techniques.

This Lunar Analogue facility is mainly intended as a 'Mission-Focused-Analogue', i.e. for highly integrated simulations with robots and humans, to test mission scenarios, stress timelines and operations, examine remote operations and procedures, and to train astronauts for lunar surface operations. However, individual components of the analogue facility can also be used for research or V&V work in a more specific area, e.g. the regolith testbed for testing rovers, ISRU processes or 3D printing, the Habitat for testing ECLSS components and aspects of habitability and Human Factors, etc.

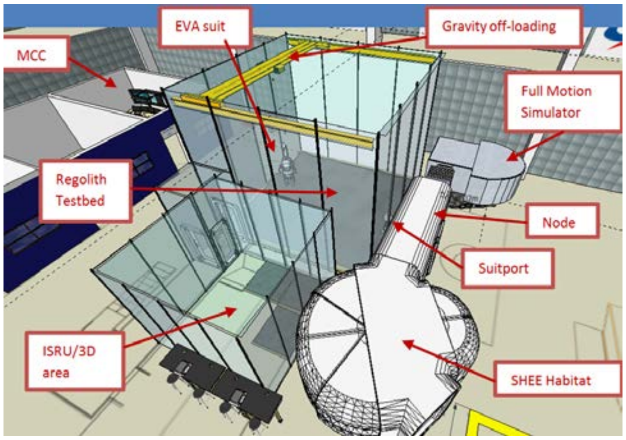


Figure 4 EAC/DLR artificial analogue concept (:envihab, NBF and big rover testbed not shown)

Based on the three broad concepts, which were presented at the Mid-Term-Review of the study, ESA has selected the EAC/DLR Analogue Concept for further consideration with respect to refining the technical concept, establishing utilisation scenarios and implementation concepts. This analogy facility is referred to as the '<u>European Surface Operations Laboratory' or 'ESOL'</u>. This Lunar Analogue facility is mainly intended as a 'Mission-Focused-Analogue', however, the analogue is also considered a Laboratory, in the widest sense of the word, where research and training can be performed. The acronym ESOL also hints to the Latin name for the Sun "Sol", a term also used to refer to solar days on extra-terrestrial bodies.

One of the ESOL Unique Selling Propositions (USP) is that this Artificial Analogue is designed such that the habitat and full motion simulator are completely integrated with the regolith simulant testbed via a suit port module. I.e. astronauts can enter/exit the regolith simulant testbed from/to the habitat or the traverse simulator and perform EVA surface operations activities in their EVA suit mock-ups without having to enter in the 'outside world'. **Another USP is the availability of a gravity off-loading device in combination with a regolith simulant testbed, which is covering a worldwide gap in Analogue infrastructure.**

In the ESOL concept, the :envihab facility can be used for doing pre- and post-simulation BDCs (Baseline Data Collection), for isolation studies that leverage the operational fidelity of the analogue at EAC, for simulating crew in a cis-lunar habitat (in the 'living and simulation area' of :envihab) and crew on the lunar surface (in the SHEE habitat at EAC) or for researching the effects of exploration atmospheres on crew.

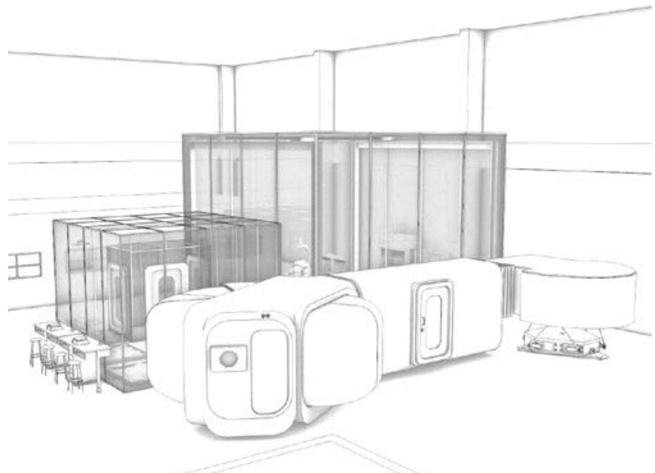


Figure 5 European Surface Operations Laboratory – ESOL

VI. UTILISATION SCENARIOS FOR ESOL

VI.I Potential users of ESOL

A wide variety of potential users is envisaged, from universities and research centres, over science and industrial communities, to traditional space agency users:

- <u>ISRU users:</u> In-Situ Resource Utilisation; testing excavating and processing technologies (extraction of oxygen and water) for dry and icy regolith, and civil engineering (3D printing, construction, etc.).
- <u>Robotics + tele-operations users:</u> deploying robots performing a variety of tasks (assembly, sample processing, etc.); studying the impact of communication constraints and delays on tele-operations.
- <u>Dust prevention and mitigation users:</u> studying dust prevention and mitigation on EVA suits, habitats, but also on rovers, etc.
- <u>Systems + Operations V&V users:</u> verification and validation of new systems, procedures, operations concepts, involving representative crew, mission control and communication constraints and delay.
- <u>EVA Tasks and Tools users:</u> partial gravity evaluation of different EVA tasks (short traverses in EVA suit, drilling, hammering, coring, etc.); ergonomy tests of EVA tools; training astronauts for lunar surface operations.
- <u>ECLSS users:</u> testing (semi-)closed loop ECLSS, with crew in the loop.
- <u>Behavioural Health and Performance (BHP) users:</u> conducting and supporting research to reduce the risk of behavioural and psychiatric conditions of a TBD sized crew in isolation; studying performance decrements due to inadequate cooperation and communication

within a team and the risk of errors due to fatigue resulting from sleep loss or work overload.

- Human factors and habitability users: addressing the challenges of long-term space habitation on extra-terrestrial surfaces. Studies about how equipment, spacecraft design, tools, procedures, and nutrition can improve the health, safety, and efficiency of crew. Further, regarding habitability variables such as interior layout, work scheduling, sleep cycles, leisure time, and communications and how to model them to improve team performance in the space environment can be tested.
- Medical users: studying medical conditions of a crew in isolation, in a controlled environment (pressure, light spectrum, day-night rhythm, etc.), following a specific nutrition diet, and faced with a certain workload and exercises (such studies could be supported by :envihab)
- STEM users: offering laboratory/hands-on experiences to high school and university students; using ESOL as a place for Master Thesis and PhD students to perform scientific and/or technological research.
- Cultural and artistic users: fostering and expanding the human and cultural aspects of space exploration, and communicating with a reach beyond traditional space-related channels. Artists and cultural professionals can be ambassadors for human expression, experimentation and exploration.

VI.II ESA HERACLES / HOPE-1 simulations

HERACLES (Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science) is an ESA-led project preparing for Moon robotics tele-operations from a cis-lunar habitat. The HERACLES Operations Preparation Experiment (HOPE-1) is a ground-only experiment focusing on the rover operations part; it is conceived as a 7-days simulation with one crew member in the analogue habitat, performing rover tele-operations as part of his/her representative daily schedule (exercise, maintenance, meals) and isolated from the outside world, except for voice and data links with the Mission Control Centre. **The HOPE-1 preparatory runs could be performed entirely at ESOL, involving the SHEE Habitat, Mission Control Centre (incl. delayed communications) and the large rover testbed.**

VI.III Yearly ESA-organised integrated analogue mission

Once a year an **ESA organized two-week integrated analogue mission simulation is proposed for ESA technology testing, Behavioural Health and Performance research and crew/ground personnel training purposes.** For this yearly integrated analogue mission simulation the crew could be selected from the current ESA astronaut corps and volunteers from the International Partners astronaut corps (similar to the selection of the crew for the CAVES and NEEMO analogues).

This yearly analogue mission simulation could typically be used for testing/validating new operations concepts. ESA/ESTEC personnel would have the **opportunity to test and operate their hardware developments in an operational context**: ECLSS systems (e.g. Water Treatment and Black Water Treatment breadboards, or the Microbial Detection in Air System for Space MIDASS) in a habitat with a two to four person crew, dust mitigation technologies, ISRU systems with icy regolith and chemical fidelity regolith simulants (e.g. the Lunar PROSPECT drill and payload for thermochemical extraction of volatiles), rovers locomotion with physical fidelity simulants, and tele-operation over delayed and bandwidth throttled communication links. **See also Figure 9 for an example of an integrated analogue mission scenario in ESOL.**

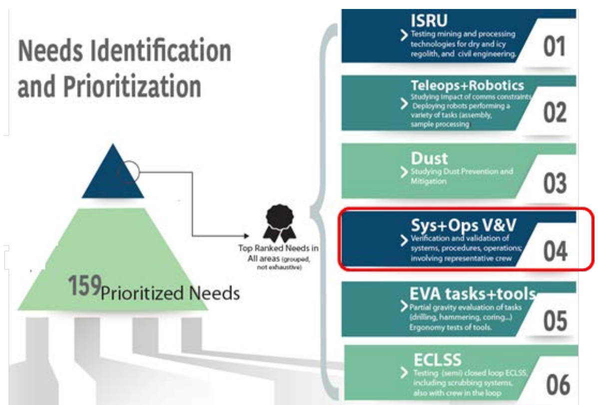


Figure 6 Extract of the Needs Identification infograph (on page 4) highlighting the importance of Systems and Operations Verification and Validation in an operational environment with crew in the loop

ESA/EAC could develop towards the Human Space Missions operations knowledge centre of ESA and would be able to test and validate new operations concepts proposed by Working Groups and Industry involved in the development of exploration architecture and ConOps for planetary missions: varying number of IV and EVA crew, different communication strategies taking into account communication delays, evaluating different EVA Tasks & Tools (from geology to IT), and human-robot cooperations. This aspect is highlighted by the 'Systems and Operations Verification & Validation' category in Figure 6.

Principle Investigators (PIs), researchers from academia, industry and public research institutes could be offered the opportunity to participate via open or targeted Announcements of Opportunity (AOs).

VI.IV ESA Long-term isolation studies

ESA acknowledges the **need for further isolation campaigns of up to 90 days** and has recently (summer 2015) set up for this purpose an Isolation Steering Committee. Campaigns similar to the ones performed by the NASA Human Research Program (HRP) in the HERA habitat can be conducted at ESOL with the unique capability that the analogue habitat is completely integrated via a node with the regolith simulant testbed and with the full motion simulator.

This allows for EVA surface operations activities of the crew directly from the habitat performing egress/ingress via the suitports as well as simulating long traverses in a pressurized rover, therefore **enabling isolation studies in an operationally relevant environment.** An enhancement of SHEE in terms of volume and life support, in order to host 4 to 6 crew members, would however be recommended.

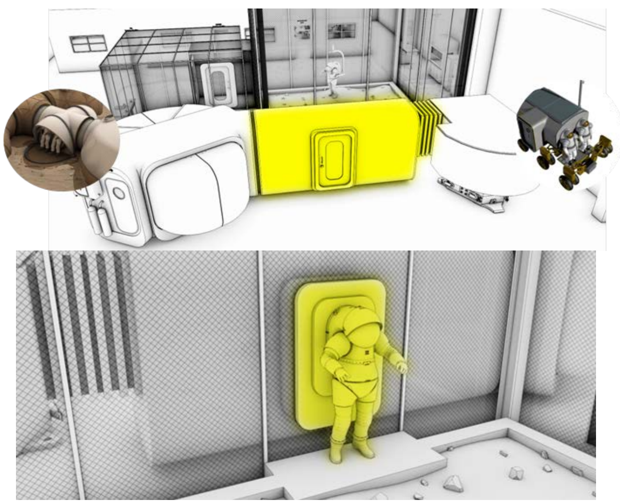


Figure 7 Habitat analogue, regolith simulant testbed and full motion simulator completely integrated via a node

VI.V Spaceship EAC utilisation

The main objective of ‘Spaceship EAC’ is to develop operational concepts and low-TRL-technologies in support of Human Spaceflight exploration missions (with specific focus on lunar habitation scenarios).

Recently the ‘Spaceship EAC’ project has gathered some strong momentum. In May 2015, the Spaceship EAC team had 15 members (13 interns or PhD students, 1 ESA staff and 1 full time research fellow). In the coming years Spaceship EAC aims to attract yearly 30-50 Master thesis and/or PhD students, under supervision of 2-3 ‘research fellows’. Currently on-going projects are covering energy research (e.g. lunar based fuel cell system, energy storage using lunar regolith), additive manufacturing via processing and sintering of lunar regolith, water purification and recycling (e.g. hydroponics and plant growth experiment with DLR), and simulation/habitability research (e.g. virtual lunar base and EVAs).

The ESOL lunar regolith simulant testbed, the SHEE habitat, the Virtual Reality Surface Simulator and the System Level Simulator would allow bridging research and operations for the Spaceship EAC projects.

VI.VI German Aerospace Centre (DLR) utilisation

The ESOL facility, being proposed for the DLR site in Cologne, would stimulate the ‘on-site’ research groups in testing and validating new technologies. For this purpose the ESOL facilities would be used in a non-integrated fashion, i.e. as a laboratory or testbed. A good example is the **DLR Institute of Materials Physics in Space which could make use of the regolith testbed with high fidelity physical and chemical lunar regolith simulants for testing ISRU processes like 3D printing.** DLR is already performing an ESA GSTP study about ‘a building block to test 3D printing of a future lunar base’ and leads the consortium in the European Union H2020 RegoLight project about ‘automated 3D printing via sintering of lunar regolith simulant with solar light’.

Also with the medical research groups at DLR there would be a cross-fertilisation: **ESOL offers complementary facilities to :envihab for tests with humans.** E.g. an integrated simulation can be conducted in ESOL and test subjects can be examined in :envihab (pre- and post- Baseline Data Collections).

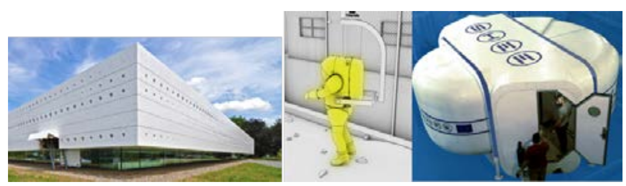


Figure 8 ESOL and :envihab integrated simulations for simulations with humans

VI.VII STEM utilisation

The **International Space University (ISU)** is interested in the field of analogue simulation for educational purposes. It could be proposed to ISU to organize a yearly ‘three-day Analogue Simulation Campaign’ as part of the MSc curriculum or Space Studies Programme (SSP) hosted in Strasbourg, France. This way **students could get the full overview of what a space mission to the Moon/Asteroid encompasses, they could act as analogue astronauts in the habitat and during EVAs, but also as operators in the Mission Control Centre** (Flight Director, Crew Communicator, Robot Operator, etc.).

Shorter sessions could be proposed for **high schools and universities around Cologne.**

A **yearly lunar rover competition could be organized in the regolith testbed / rover testbed** of the ESOL. In analogy with NASA's Robotic Mining Competition on an analogue Martian terrain, the ESA Lunar Rover Competition could target university-level students and could challenge them to design and build a mining robot that can traverse the simulated Lunar terrain. The rover could for example excavate the lunar regolith simulant and the icy regolith simulant and return the excavated mass for deposit into a sample box.

VI.VIII Commercial utilisation

ESOL could be offered to **companies/industry** on a commercial basis for research or demonstrations in an operational lunar analogue environment.

VI.IX Public outreach

Being located on the DLR site in Cologne and focused in and around the European Astronaut Centre (EAC), the ESOL facility would have a big potential for public outreach activities. With the prospect of having a European astronaut flying to the International Space Station every year for the coming years and with the objective of EAC to further establish itself as one of the top-three centres in the world for astronaut training and human spaceflight medical operations, the EAC and the ESOL facility will have a **high visibility towards International Partners, researchers and the general public**. Furthermore, almost daily guided visits to the DLR research laboratories and the EAC facilities are organised and the bi-annual German Space Day attracts up to 60,000 visitors.

While the ESOL facility and components are in the first place designed to be functional and to address the identified needs, they are also visually attractive, hence it would be a perfect and inspiring location for PR events (e.g. TED talks, public lectures).

VII. IMPLEMENTATION ASPECTS

VII.I Phased implementation approach

The implementation of ESOL foresees a phased approach in order to accommodate budget constraints (spreading the implementation costs over a longer timeframe), while ensuring that the first phase of implementation and the growth or evolution path of the ESOL reflects the most promising utilisation scenarios. Components and ROM cost estimates per implementation phase are given in Table 1.

Phase 1 includes the SHEE habitat analogue (for 2 persons), the regolith testbed, the large rover testbed and MCC (incl. delayed communications). Hence, the Phase 1 implementation would allow short duration studies with small crews in a highly integrated analogue setting. Implementing the regolith testbed and the large rover testbed in Phase 1 reflects the Spaceship EAC utilisation scenario, the DLR-RegoLight utilisation scenario and the HERACLES/HOPE-1.A utilisation scenario.

The regolith simulant testbed should be the first component to be implemented (potentially already in a pre-phase 1) as it is addressing most of the 'driving needs' and it is for the public a highly visible component (i.e. a 'footprint of the lunar surface').

Phase 2 includes the adaptation of SHEE to provide a simulation platform for short term isolation studies with crews of 2 to 4. Furthermore the Full Motion Simulator and the Partial Gravity Off-Loading device would be added. Both additions are enlarging the analogue simulation capabilities and allow even more integrated simulations. The addition of the Partial Gravity Off-Loading device in combination with the regolith testbed would close a worldwide gap in analogue capability. Hence, the implementation of Phase 2 provides better analogue capabilities for the ESA/International Partners Integrated Analogue Mission Simulation and the ESA/International Partners Isolation Studies utilisation scenarios.

Phase 3 –consisting of the implementation of a full-fledged second habitat and food growth facility– would finally allow implementing the Isolation Studies Scenario, i.e. isolation of up to 90 days in the Habitat, with crews of 4 to 6 (this would meet the current requirement for European Isolation studies).

ESOL ANALOGUE MISSION SIMULATION SCENARIO - EXTRACTION OF VOLATILES FROM ICY REGOLITH								
Day	**Activity Description**	**MCC**	**Habitat**	**Suit port**	**Regolith Testbed**	**Suit port**	**Rover Simulator**	**Objectives**
PRE	**Pre-Baseline Data Collection in :envihab**							
#1	1. Tele-operation of a scouting rover from cis-lunar space station 2. (Overnight) travel to lunar surface	**Mission Control Centre support** (comms delays and bandwidth limitations)	4 crew in :envihab		Scouting rover on regolith testbed			a) Train and evaluate different tele-operations technologies (with comms delay and bandwith limitations) b) Evaluate fatigue
#2	1. Base activity / settling in 2. Habitat inspection & testing functions (IVA) 3. Prep rover traverse (incl. path planning, camping toilet, food, sleeping bags, etc.)		2 crew sleep in SHEE (4 crew for eating, hygiene, work) + Technology Demonstrator				2 crew sleep in Rover Simulator (eating, hygiene, work, etc. in SHEE)	a) Checking out habitat main systems (e.g. power, ECLSS, data/comms) b) Checking out & preparing EVA suits c) Checking out pressurised rover d) Evaluate fatigue
#3	1. Long traverse with Pressurised Lunar Rover		2 crew in SHEE, going for EVA + Technology Demonstrator	⇨ ⇦	**LIGHT (South Pole base)** EV1 in partial gravity EV2 in 1G Rover supporting EVA (item carry, others)		2 crew in Rover Simulator, Virtual Reality simulation of long lunar traverse (to Permanently Shadowed Region - PSR)	a) Evaluate task performance in partial/full G and full light b) Train ingress/egress & evaluate dust mitigation techniques c) Evaluate dust contamination on Tools
#4	2. Construction/assembly task 3. Astronaut - robot cooperation		2 crew in SHEE, going for EVA + Technology Demonstrator	⇨ ⇦	**LIGHT (South Pole base)** EV1 in 1G EV2 in partial gravity Rover supporting EVA (item carry, others)		2 crew in Rover Simulator, Virtual Reality simulation of long lunar traverse (to Permanently Shadowed Region - PSR)	d) Evaluate different HMIs for astronaut - robot cooperation (e.g. gesture control, chest/wrist display) e) Evaluate fatigue
#5	1. Install scientific payloads (e.g. RAMAN spectrometer, small antenna dish, PROSPECT) 2. Picking up samples & stowing them in bags		2 crew in SHEE + Technology Demonstrator		**DARK (PSR)** EV3 in partial gravity EV4 in 1G	⇦ ⇨	2 crew in Rover Simulator, going for EVA	a) Evaluate task performance in partial/full G and in darkness b) Train ingress/egress & evaluate dust mitigation techniques c) Evaluate different Tools and dust contamination on them
#6	3. Drilling/coring in icy regolith (Lunar PROSPECT drill) up to 1m deep 4. In-situ analysis / extraction of volatiles from icy regolith operating Lunar PROSPECT payload		2 crew in SHEE + Technology Demonstrator		**DARK (PSR)** EV3 in 1G EV4 in partial gravity	⇦ ⇨	2 crew in Rover Simulator, going for EVA	d) Technology and operations test of lunar PROSPECT drill & payload e) Evaluate fatigue
#7	1. Tele-operating of TBD rover/robot from lunar habitat 2. Long traverse with Pressurised Lunar Rover		2 crew in SHEE + Technology Demonstrator		Rover/robot on regolith testbed		2 crew in Rover Simulator, Virtual Reality simulation of long lunar traverse (back to habitat)	a) Train and evaluate different tele-operations technologies b) Evaluate fatigue
#8	1. EVA suit maintenance 2. Long traverse with Pressurised Lunar Rover		2 crew in SHEE, 1 going for EVA + Technology Demonstrator	⇨ ⇦	**LIGHT (South Pole base)** EV1 in partial gravity 2nd crew in SHEE supporting from inside the suitport		2 crew in Rover Simulator, Virtual Reality simulation of long lunar traverse (back to habitat)	a) Train and evaluate EVA suit maintenance procedures b) Train ingress/egress c) Evaluate fatigue
#9	1. Analysis of collected samples 2. Planning return to cis-lunar habitat (configuring habitat to stay abandonded) 3. (overnight) travel to cis-lunar habitat		2 crew sleep in SHEE (4 crew for eating, hygiene, work) + Technology Demonstrator				2 crew sleep in Rover Simulator (eating, hygiene, work, etc. in SHEE)	a) Evaluate fatigue
POST	**Post-Baseline Data Collection in :envihab**							

Figure 9 Example ESOL Utilisation Scenario for a highly integrated mission simulation with the science objective to extract volatiles from icy regolith

	Pre-Phase 1	Phase 1	Phase 2	Phase 3
Regolith Simulant Testbed	x			
SHEE Habitat		x	Enhancement (airtight)	Second SHEE
System Level Simulator		x		
EVA, IVA. MCC Information System		x	Enhancement	
EVA Hardware (suit + tools)		2 suits	High fidelity EVA Tools	
Compatible Robot Control Station		x	Enhancement	
Control Room Facilities		x		
Ingress/egress interfaces		x		
Treadmill + VR goggles		x		
Full Motion Simulator			x	
Food Growth Facility				x
Gravity Off-Loading Device			x	
~1000sqm Rover Testbed		Basic facility	Enhancement	
Total ROM Cost	360k€	2.4M€	1.8M€	1.8M€
Utilisation scenarios	• ISRU, Dust • Robotics, Tele-robotics	• HERACLES / HOPE-1 preparatory simulations • ISRU, Dust • Robotics, Tele-robotics • ECLSS (only water recycling)	• EVA Tasks & Tools • ECLSS (air & water)	• Long Duration Isolation Studies (up to 90 days) • ECLSS (air, water, food)
Timeframe	2016	2017	2018	2020

Table 1Phased implementation approach for the ESOL facilities

VII.II Daily operations implementation recommendations

It is recommended that EAC provides **1 FTE technician and 1 FTE scientific person** (also administrative) responsible for the continuous running of the ESOL facility (technical operations and maintenance), for the acquisition of users, knowledge transfer, programmatic supervision and outreach towards the user community and the public. **In addition to the personnel a ROM cost of 300kEuro/year has been estimated for the running costs of the facility (consumables, maintenance and minor upgrades of existing facility).**

Running analogue missions in ESOL could be heavily supported by Spaceship EAC personnel. Besides doing their own research in ESOL, the Spaceship EAC personnel could be tasked with operating the facility and supporting external users, as well as with upgrading the ESOL facilities.

ESOL could **grant access free of charge to visiting scientists in exchange for student tutoring, knowledge transfer and/or hardware contributions.** Access to industrial/commercial users may be granted at full cost.

A European Analogue Working Group should be established (taking into account NASA's experience with its 'Flight Analogs Projects Office'). This Working Group should propose evidence-based research issues connected to operations and to coordinate efforts based on objectives across ESA centres (technology tests, training, operations research, scientific research). The ESOL scientific person should be mandatory member of this European Analogue Working Group.

VIII. CONCLUSION

The **'European Surface Operations Laboratory' ('ESOL') proposed to be implemented at the DLR/EAC site in Cologne**, has been identified as the most promising lunar analogue concept in order to properly address several of the identified gaps in Analogue infrastructure and to enhance Europe's capabilities within the international effort of exploring the Moon.

The ESOL facility is designed in first place as a Lunar Analogue facility, however, the concept is extendable to other planetary destinations.

The ESOL facility is mainly intended as a *'Mission-Focused-Analogue'*, i.e. for highly integrated simulations with robots and humans, to test mission scenarios, stress timelines and operations, examine remote operations and procedures, and train astronauts for lunar surface operations. Relevant facilities already available at EAC and the DLR Campus, as well as the **specialised human capital at EAC**, i.e. directly relevant expertise and know-how from the astronauts, astronaut instructors, flight surgeons, astronaut medical support team, and education & outreach people, are strong assets in support of the objectives of the ESOL facility.

One of the ESOL Unique Selling Propositions (USP) is that this Artificial Analogue is designed such that the habitat and traverse simulator are completely integrated with the regolith simulant testbed via a suit port module. I.e. astronauts can enter/exit the regolith simulant testbed from/to the habitat or the traverse simulator and perform EVA surface operations activities in their EVA suit mock-ups without having to enter in the 'outside world'. **Another USP is the gravity off-loading device in combination with a regolith simulant testbed, which is covering a worldwide gap in Analogue infrastructure.**

Although one of the Unique Selling Points is the integrated context of the regolith simulant testbed, the habitat and the rover simulator, **if one component needs to be selected to be built first, it should be the regolith simulant testbed.** This component is addressing most of the 'driving needs' and at the same time it is for the public a highly visible component (i.e. a 'footprint of the lunar surface'). It can be considered the 'core' of the ESOL facility around which later-on the other components can be built.

The ESOL Artificial Analogue concept is backed-up by a variety of utilisation scenarios, which address the 'driving Needs' of Lunar surface operations identified by more than 100 international Subject Matter Experts (SMEs) and by analysis of relevant technology Roadmaps, reference missions and literature.

IX. ACKNOWLEDGMENTS

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