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ANALOGUES FOR PREPARING ROBOTIC AND HUMAN EXPLORATION ON THE MOON

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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, as they allow improving controllability of the environment and 'standardising' the Analogue in order to allow a meaningful comparison between several simulation campaigns, increasing actual test time, while reducing preparation overhead and logistics costs, with respect to 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 paper 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. Furthermore, the paper provides the three different Artificial Lunar Analogue concepts proposed 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. The paper concludes with a preliminary overview of potential users and utilisation scenarios, for the Artificial Analogue concept which was selected by ESA.

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 and whose infrastructure can be adapted to fully Artificial Analogues, or whose accessibility and logistics burden may be lower than a typical natural analogue in a remote location. Examples of what can be considered a Mixed Lunar Analogue 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.

Besides the obvious advantages of the Natural Lunar Analogues, i.e. terrain, soil and harsh environment (dust, temperature, psychological effects, etc.) are representative for the lunar environment and do not need to be artificially recreated, there is the *'logistics disadvantage'* of Natural Lunar Analogues. Carrying out tests, demonstrations or training in Natural Lunar Analogues comes with a big effort and cost simply to go and deploy the people and the technology on the often remote analogue site. Furthermore, a lot of practicalities need to be taken into account for these remote outdoor sites, e.g. provision of electricity and telecommunications capability, weather factors and deployment of temporary infrastructures (e.g. tents), and depending on location also visa and custom procedures, which can lead to increased costs and potential delays of the test/training campaign.

Therefore, there is a **growing interest in Artificial Lunar Analogues** in order to avoid the *'logistics disadvantage'* of the Natural Lunar Analogues. The main advantages 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, will result in improved test quality.
- Significantly reduced logistical preparations and costs compared to simulation campaigns in Natural Analogues.
- Significantly increased test-time compared to Natural and Mixed Analogues, because reduced logistics (easy access) and costs will allow more test runs.
- Easier access and lower cost will 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.

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 existing Artificial Lunar Analogues in Europe and worldwide, consider potential synergies in utilising these facilities and to propose new Artificial Lunar Analogues as a response to the needs identified for such analogues. This approach will help to identify simulation means where ESA might need to develop capabilities but also identify where ESA can build up facilities that might be a future contribution of the international effort of exploring the Moon in the future.

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.

II. NEEDS ANALYSIS

II.I Needs identification and classification

To begin with, a Needs Database was drawn from the NASA Space Technologies Roadmap[3], ESA 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 conferences.

The roadmaps tend to focus heavily on technology developments and they do not focus so much on the area of "Human Research". The study team compensated for this by adding data from the NASA Analogue Assessment Tool Report (AATR)[7] to the Needs Database. 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.

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

The last, but very valuable, source of inputs for the Needs Database were the inputs from 106 Subject Matter Experts (SMEs) from all over the world who 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.

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) are analogous to Technical Features (TFs) except they concern only the subject of BHP research. They are considerations, mostly connected to the fidelity of simulation campaigns rather than to the Analogue infrastructure, necessary in order to satisfy the BHP Needs. They were identified based on the AATR[3]. TFs and FCs were proposed by the study team in order to indicate how each identified Need can be addressed. I.e. a certain Need can only be fully addressed by a certain Artificial Analogue, when the Analogue contains the right combination of Technical Features and Fidelity Characteristics.

II.III Subject Matter Expert (SME) survey

Following this preliminary identification of Needs, Technical Features and Fidelity Characteristics, an online survey was issued with the objective of validating the Needs (identified by the study team in roadmaps and technical papers) as well as the TFs and FCs proposed to address the identified Needs, and to solicit Subject Matter Experts (SMEs) for additional Needs, TFs and FCs.

The survey was conceived in a targeted manner, that is, most respondents were selected one by one, and dissemination of the survey was limited. The survey was, by design, made to be as general as possible due to the breadth of disciplines involved. A matrix matching fields of expertise and type of institution was designed in order to have a good distribution of the experts among academia & non-profits (36%), industry (17% large space companies, 11% small and medium-sized enterprises), Space Agencies (20% ESA and European National Agencies, 11% non-European Agencies) and others (5%).

The survey was considered highly successful with 106 SMEs –out of 276 invited SMEs– responding to the questionnaire. The replies came mostly from European countries as most of the surveyed individuals are connected with ESA, however several experts in foreign agencies and other non-European Institutions showed great interest and provided very relevant responses.

In order to do a meaningful analysis of the answers from the SMEs, the SMEs were divided into three main groups (user populations): Exclusively Human Spaceflight (combining the areas 'habitat design', 'BHP', 'crew health', 'environmental control and life support systems', 'operations' and 'training') [53 SMEs], Exclusively Robotics [8 SMEs], and Human Spaceflight + Robotics [26 SMEs]. From the 106 SMEs who responded to the survey only 19 could not be distributed in one of these three groups.

After the finalisation of the Subject Matter Expert survey and throughout the subsequent phases of the Lunar Analogues study 10 SMEs have been consulted for further in depth interviews and overall advice with respect to the proposed Artificial Analogue concepts.

II.IV Needs significance rating

A "Weighted Sum Model" was used to determine the significance rating or the 'prioritization' of the identified Needs.

The following 3 criteria and ratings were used:

- Need appears in the NASA/ESA Roadmaps or Design Reference Mission (DRM): 3 (in both ESA and NASA or ISCEG), 2 (in ESA roadmap or ESA Lunar DRM), 1 (in NASA or ISEGC roadmap), 0 (not in any roadmap).
- Need identified through relevant literature survey / technical Papers: 3 (5+ papers), 2 (3-4 papers), 1 (1-2 papers), 0 (no paper).
- Need identified by Experts in the SME Survey: 3 (>5 SMEs), 2 (>2 and <5 SMEs), 1 (<2 SMEs), 0 (no SMEs).

In agreement with ESA the following weights were given to the different criteria:

- Roadmaps: 50%
- Papers: 25%
- Experts: 25%

From the 159 identified Needs 19 Needs received a significance rating equal or higher than 2. These Needs are called the 'driving Needs' and can be categorized in 6 main groups: testing In-Situ Resource Utilization (ISRU) mining, extracting, constructing processes; Studying the impact of communication constraints (bandwidth, delay) on tele-operations and robotics deployment; Dust prevention and mitigation; Verification and Validation of systems, procedures and new operational concepts; Partial gravity evaluation of Extra Vehicular Activity (EVA) tasks and tools handling; Testing (semi-)closed loop Environmental Control and Life Support Systems (ECLSS). See Figure 1.

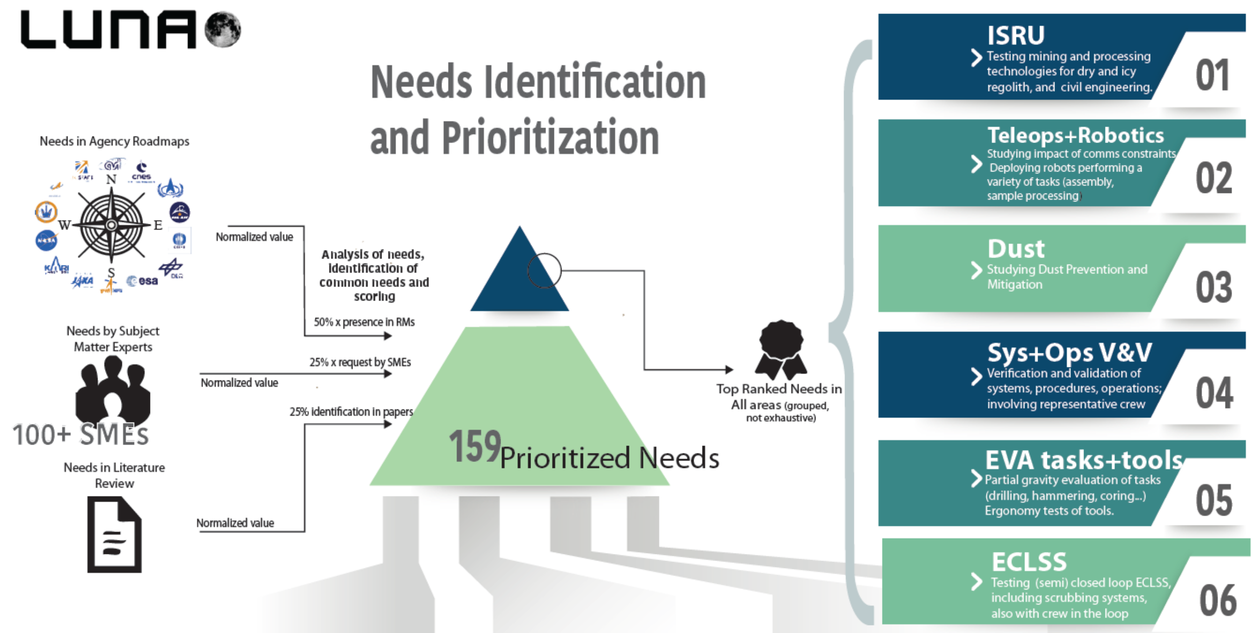

Figure 1 Establishment of Needs Database and Prioritization, resulting in 'driving Needs' in 6 main groups

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 ESA-state facilities, but gives an overview on facilities available worldwide.

The Artificial Analogues catalogue should be considered complementary to past ESA studies, such as "Concepts for Activities in the Field for Exploration (CAFE)[2]" that listed some 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 but that are hosted in a controlled environment and thus require less logistic efforts for setting up a simulation. 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.

Mixed Analogues (e.g. NASA's Deep Space Habitat or the European Self-deployable Habitat for Extreme Environments – SHEE) have been included in the Artificial Analogues catalogue.

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 in countries like China, Russia and India, but the data on those are sparse or simply not available publicly.

The survey and geographic mapping of facilities showed that in Europe, there 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 means of the Technical Features and Fidelity Characteristics, which were already introduced for the establishment of the Needs Database.

IV. GAP ANALYSIS

IV.I Needs vs. Analogues mapping matrix

The methodology used to establish a valid process for both identifying and analysing the gaps in current Artificial Analogue infrastructure plus eventually to create new concepts to address these gaps is based on attributing Technical Features (TFs) and Fidelity Characteristics (FCs) to the identified Needs and the characterization of the Artificial Analogues by exactly the same TFs and FCs. Theoretically, a facility that possesses all the TFs and/or 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, individually linking the 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 of 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 2. This matrix contains the percentage of TFs or FCs that each facility satisfies, per Need. E.g. an Analogue which scores 100% for a certain Need, fully addresses the identified Need; an Analogue which scores 30% for a certain Need, means that the Analogue contains only 3 out of 10 necessary Technical Features/Fidelity Characteristics in order to fully address that specific Need.

IV.II Gap Analysis results

Following the Needs significance rating and subsequent analysis, which ensured that the 19 'driving Needs' (Needs with a significance rating equal or above 2, see section II.IV) provide a good coverage of the different groups of Needs, the detailed gap analysis has been performed on these 'driving Needs'. The following provides an overview of the identified gaps.

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. For this habitat/vehicle egress/ingress facilities need to be available, operating in a context involving regolith simulant, also electrostatically charged. Furthermore, the habitat will allow (semi-)closed loop ECLSS research and demonstration, e.g. for the European MELISSA, and BHP related research.

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 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.

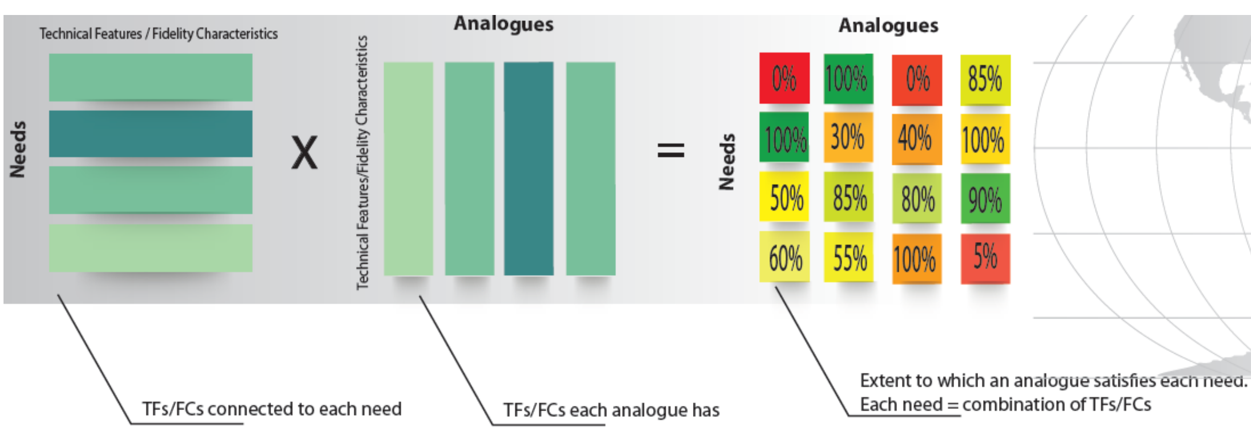

Figure 2 Gap Analysis methodology: creation of the 'Needs vs. Analogues mapping matrix'

V. ARTIFICIAL LUNAR ANALOGUE CONCEPTS

The gap analysis performed resulted in the identification of gaps (see section IV.II), but it also gave an indication which Analogue Facilities in Europe already have a good potential (i.e. address several Needs of the user community) and thus are considered 'prime locations' to implement a more complete Artificial Lunar Analogue Facility. The 3 locations for which an Artificial Analogue Concept as part of this study was proposed are:

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

V.I 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, 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 an enormous 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), gravity off-loading system (for humans, compatible with the EVA suit mock-ups, and for rovers), system level simulator, traverse simulators (6 degree of freedom simulator with a virtual reality rendering of the lunar surface), Mission Control Centre (MCC), 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 will 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. 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.

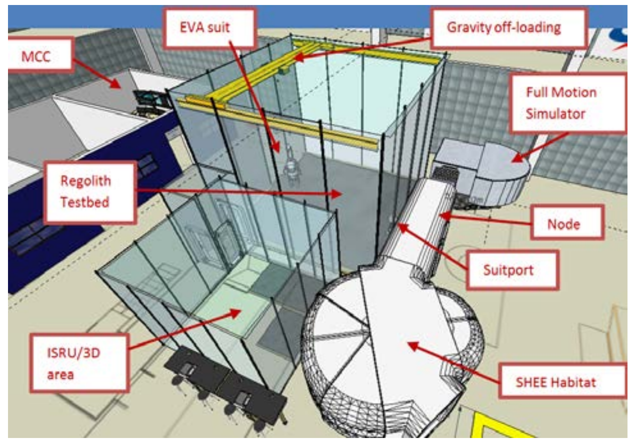

Figure 3 EAC/DLR artificial analogue concept (:envihab, NBF and big rover testbed not shown)

V.II 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 and life support system testing.

The habitat section of Hydrosphere has a volume close to the volume of ESA's Columbus laboratory at ISS. It can be used to test life-support systems (in closed or semi-closed loop). The installation, furthermore, 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.

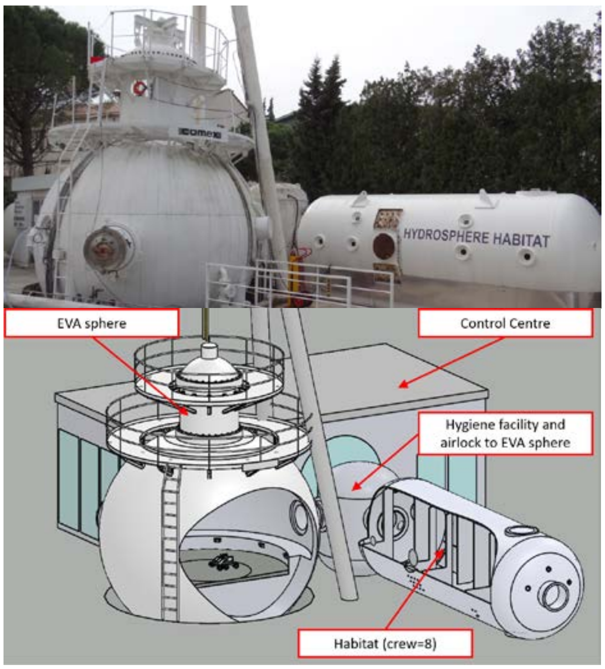

Figure 4 Hydrosphere artificial analogue concept

V.III 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 max. 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 5 Mars Moon Terrain Demonstrator (MMTD) [Image courtesy ALTEC S.p.A.]

V.IV ESA Selected Artificial Lunar Analogue: ESOL

ESA has selected the EAC/DLR Analogue Concept for further consideration with respect to establishing utilisation scenarios and implementation concepts.

The selected Artificial Analogue is designed mainly as a Lunar Analogue facility, however, the concept is extendable to other planetary destinations, in compatibility with the identified needs of the world Subject Matter Experts (SMEs), and in particular the European community; also highlighting its validity across evolving or changing priorities, in any case as an analogue devoted to surface operations.

The EAC/DLR Analogue Concept will be referred to as **'European Surface Operations Laboratory' or 'ESOL'**. 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, 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 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 availability of a gravity off-loading device in combination with a regolith simulant testbed, which is a worldwide gap in Analogue infrastructure.

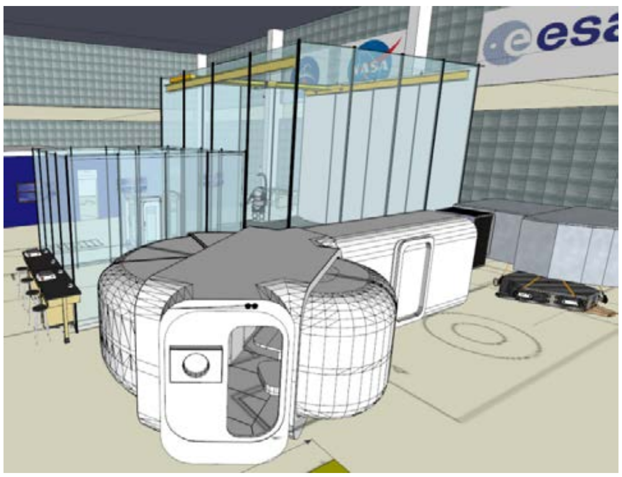

Figure 6 European Surface Operations Laboratory – ESOL (3D sketch of the Analogue facility)

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 lunar orbiter (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.

VI. UTILISATION SCENARIOS

VI.I Potential users

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

- ISRU users: 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.).
- Robotics + tele-operations users: deploying robots performing a variety of tasks (assembly, sample processing, etc.); studying the impact of communication constraints and delays on tele-operations.
- Dust prevention and mitigation users: studying dust prevention and mitigation on EVA suits, habitats, but also on rovers, etc.
- Systems + Operations V&V users: verification and validation of new systems, procedures, operations concepts, involving representative crew, mission control and communication constraints and delay.
- EVA Tasks and Tools users: partial gravity evaluation of different EVA tasks (short traverses in EVA suit, drilling , hamering, coring, etc.); ergonomy tests of EVA tools; training astronauts for lunar surface operations.
- ECLSS users: testing (semi-)closed loop ECLSS, with crew in the loop.
- Behavioural Health and Performance (BHP) users: 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 exercices.
- STEM users: as part of STEM education the ESOL can provide valuable laboratory/hands-on experiences to high school and university students and can become 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 offer means of communication with a reach beyond traditional space-related channels. Artists and cultural professionals can be ambassadors for human expression, experimentation and exploration.

VI.II Utilisation scenarios

The below presented utilisation scenarios are preliminary proposals from the study consortium towards Agencies, STEM users, etc. Given the nature of the current Lunar Analogues project – conceptual design study and feasibility – none of the below utilisation scenarios have been translated into agreements with or real commitments from the potential users.

ESA and International Partners utilisation

Once a year an ESA organized two-week integrated analogue mission simulation is proposed for ESA technology testing, BHP 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 would typically be also used for testing/validating new operations concepts. ESA/ESTEC personnel will have the opportunity to test and operate their hardware developments in an operational context: ECLSS systems in a habitat with a two to four person crew, ISRU systems with chemical fidelity regolith simulants, rovers locomotion with physical fidelity simulants, and tele-operation over delayed and bandwidth throttled communication links.

ESA/EAC could grow as 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, adequacy of tools (from geology to IT), human-robot cooperations, and others.

Principle Investigators (PIs), researchers from academia, industry and public research institutes would be offered the opportunity to participate via open or targeted Announcement of Opportunities (AO) to include new interesting experiments or answers to focused questions.

Spaceship EAC utilisation

Recently the ‘Spaceship EAC’ project has gathered some strong momentum after a slow starting phase in the last few years. 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’. In May 2015, the Spaceship EAC team contained 15 members (13 interns or PhD students, 1 ESA staff and 1 full time research fellow).

The aim of ‘Spaceship EAC’ is to:

- **“Foster exploration activities in ESA”**
  EAC involvement in triggering R&D by students of new Human SpaceFlight (HSF) technologies will accelerate exploration and improve quality of results.
- **“Operate: Showcase & technology incubation platform”**
  EAC as operational testbed for future technologies (space and Earth applications) to demonstrate at a low TRL processes or technology, already in an integrated fashion.
- **“Support exploration relevant research”**
  Networking with external researchers across the EU to bridge the gap between research and operations.
- **“Inspire”**
  Inspire students by offering internships in EAC and networking with universities, inspire the public by active outreach, and inspire ESA / national agencies by networking and Announcements of Opportunities (AO).

Interning students part of the ‘Spaceship EAC’ team could support the utilisation of such analogue (world-class facilities to perform their internship research/project) and would increase the staff effort available at EAC to sustain the analogue’s operability.

DLR utilisation

The ESOL facility, being located on the DLR site in Cologne, will stimulate the ‘on-site’ research groups in testing and validating new technologies. For this purpose the ESOL facilities will 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 can make use of the regolith testbed with high fidelity physical and chemical lunar regolith simulants for testing ISRU processes like 3D printing or water/oxygen extraction processes.

STEM utilisation

Personnel of the LUNA consortium, from Space Applications Services, has been involved with the **International Space University (ISU)** in the development of educational analogues, in which the students consolidate their knowledge on space operations by executing a number of challenging tasks that require teamwork, and proper planning among distributed teams under communications delay, driving robots and drones operating in conjunction with humans on a imaginary planetary surface. It could be proposed to ISU to organize a yearly ‘one-week Analogue Simulation Campaign’ as part of the MSc curriculum and a bi-yearly ‘one-week Analogue Simulation Campaign’ as part of the ISU Space Studies Program (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 Mission Control Centre (Flight Director, Crew Communicator, Robot Operator, etc.).

Shorter sessions (e.g. two-day sessions) could be proposed for **high schools and universities around Cologne**: the first day providing an introduction to analogues / analogue mission simulations and preparing the student analogue simulation, and the second day performing the actual simulation with distributed teams under communications delay, driving robots and drones operating in conjunction with humans on an analogue lunar surface.

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 targets university-level students and challenges them to design and build a mining robot that can traverse the simulated Lunar terrain. The rover must excavate the lunar regolith simulant and the icy regolith simulant and return the excavated mass for deposit into a sample box. The complexities of the challenge include the abrasive characteristics of the lunar regolith simulant, the dust tolerance of the rover, the weight and size limitations of the mining rover and the ability to tele-operate it from a remote Mission Control Center (with or without communication outages, delay, etc.).

Commercial utilisation

Outside the big analogue simulation campaign periods, companies/industry will be able to rent the ESOL facilities (or part of them) on a commercial basis in order to perform research or demonstrate in-house developed technologies in an operational lunar analogue environment.

Public outreach

Being located on the DLR site in Cologne and focused in and around the European Astronaut Centre (EAC), the ESOL facility has 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 guaranteed 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.

Besides the obvious STEM function of the student robotics competition, the rover competition will be an important yearly outreach event, too.

VII. CONCLUSION

The 'European Surface Operations Laboratory' or 'ESOL' Artificial Lunar Analogue concept to be implemented at the DLR/EAC site in Cologne, has been retained by ESA as the most promising concept in order to properly address several of the identified gaps in Analogue infrastructure and to put Europe in pole position to contribute to the international effort of exploring the Moon.

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. The very valuable human capital already available at EAC, directly relevant expertise and know-how from the astronauts, astronaut instructors, flight surgeons, astronaut medical support team, and education & outreach people is well in line with the objective 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 availability of a gravity off-loading device in combination with a regolith simulant testbed, which is a worldwide gap in Analogue infrastructure.

The selected Artificial Analogue is designed mainly as a Lunar Analogue facility, however, the concept is extendable to other planetary destinations, in compatibility with the identified needs of the world Subject Matter Experts (SMEs), and in particular the European community; also highlighting its validity across evolving or changing priorities, in any case as an Analogue devoted to surface operations.

The ESOL Artificial Analogue concept is strongly backed-up by a variety of utilisation scenarios (for Space Agency users, STEM users, commercial users and public outreach), which address the 'driving Needs' identified by the Subject Matter Experts (SMEs) and by analysis of the different Roadmaps and literature.

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