

Advances in the ESA-DLR LUNA Analog Facility: Updates on Users' Testing and Facility Development

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Abstract

The Artemis era has begun with the Artemis I mission in 2022: since then, NASA is working eagerly to bring back humans on the lunar surface with the Artemis III mission planned in September 2026. This renewed interest in our natural satellite since the Apollo times is spinning the wheel of innovation in many technology sectors. New partnerships and paradigms are constantly being born, especially with the involvement of private investors, thus opening the doors for a new commercial era. This revolution of the space sector is also affecting Europe, where consolidated institutions and new players are investing a considerable amount of resources.

The German Aerospace Center (DLR) and the European Space Agency (ESA) have recently partnered to build a worldwide-unique lunar analog facility named LUNA. The facility has been constructed onto the premises of the DLR Cologne campus and it is fully integrated with the operational network of the European Astronaut Centre (EAC), the German Space Operations Center (GSOC), and the Microgravity User Support Center (MUSC). The ultimate goal of the facility is to close the gaps between analog field activities and lab testing, offering to international partners, industries, research institutions, start-ups and universities a cutting-edge platform able to fully simulate on ground realistic Moon conditions such as dust, reduce gravity and peculiar lighting scenarios. The 700 m² regolith testbed area allows full robotic systems' operations and lunar Extravehicular Activities (EVAs) simulations. The realism of such activities is further enhanced by a dedicated ground segment, already connected with the existing control centres of the International Space Station (ISS) and the forthcoming lunar Gateway ones.

Training astronauts, maturing technologies, deploying infrastructures, and testing new operational concepts in analog campaigns are the key features of LUNA that allow derisking before flying to the lunar surface.

With the official inauguration of the facility in September 2024, this work presents the first results obtained during the first users' campaigns focused on human and robotic interactions. The scientific objectives and the resulting lessons learnt are presented, including a complete outlook of the utilization scenarios envisaged.

Keywords: Moon, Lunar exploration, Human spaceflight, Lunar science, Lunar operations

Acronyms/Abbreviations

European Astronaut Centre (EAC)

European Service Module (ESM)

European Space Agency (ESA)

Extravehicular Activity (EVA)

Future Lunar EXploration Habitat (FLEXHab)

German Aerospace Center (DLR)

Disruption Tolerant Networking (DTN)

In-Situ Resource Utilization (ISRU)

International Space Station (ISS)

Monitoring and Control System LUNA (MCS-L)

Mixed Reality (MR)

National Aeronautics and Space Administration (NASA)

Virtual Reality (VR)

eXtended Reality (XR)

1. Introduction

The global space sector is currently experiencing a new era of coordinated human and robotic exploration missions. Since the early 2000s, there has been a renewed interest in the Moon, which has now reached a critical point: several countries and national space agencies have initiated ambitious programs with global scientific objectives with an unprecedented focus on lunar missions [1]. New players are also entering and populating the market that is flourishing during these novel lunar renaissance times; private companies and investors are beginning to recognise the lunar economy as a potential investment to generate future revenues.

In this globally crowded framework, Europe is also preparing to play an active role in the collective lunar endeavour with the ambitious Terra^e Novae 2030+ program [2] developed by the European Space Agency (ESA). Collaborations with international partners, such as the National Aeronautics and Space Administration (NASA), are included. ESA and its member states are playing a significant role within the NASA-led Artemis program [3], notably through ESA's contribution by building the European Service Module (ESM) of the Orion capsule, which successfully completed the Artemis I mission. Additionally, ESA will substantially contribute to the Gateway station, a multi-purpose outpost orbiting the Moon as part of the Artemis program, by constructing the habitation and refuelling modules [4].

Starting from Artemis III [5], the objective of this ambitious program is to land humans on the lunar surface for the first time since the Apollo 17 mission in 1972. Cargo and logistic systems will be essential for surface operations, and ESA is actively working towards developing the Argonaut spacecraft [6] to meet this need and contribute to the global effort of establishing a permanent human presence on the Moon.

To prepare, test, and validate technologies for enabling surface activities, train astronauts, and develop concepts of operations, new facilities are required. Unlike natural analogues, closed facilities allow to control and standardise the test conditions (thus not subject to weather forecast), easing the logistic efforts related to execute simulations and test campaigns. The German Aerospace Center (DLR) has partnered with ESA to create LUNA, a worldwide excellence and unique training and testing facility for lunar mission simulations.

The present paper describes the current status of the LUNA facility and its outfitting, also presenting the first results obtained during the first test campaigns and the forthcoming installation of the missing outfitting elements.

2. The ESA-DLR LUNA analog facility

Located on the DLR Cologne-^{Porz} campus premises and next to the European Astronaut Centre (EAC), LUNA marks a major advancement in Europe's lunar research capabilities. The facility includes a main hall that accommodates technical rooms, a large regolith testbed area, and several external elements, creating a complete lunar research ecosystem. The main building is illustrated in Fig. 1.



Fig. 1. The ESA-DLR LUNA facility (credit: ESA/DLR - A. Sima)

The primary design goal of LUNA has been to address the gaps in lunar analogue facilities [7], aiming to create a novel and advanced facility that bridges field and laboratory work. Various natural and artificial analogues exist on Earth, ranging from deserts to specialized laboratories, but none fully simulates all relevant lunar conditions with comprehensive operational capabilities in an easily accessible environment like LUNA. Due to its size, location, connections with other DLR facilities, and the pool of lunar experts addressing most domains of lunar science, the portfolio of activities for mission simulations at LUNA is broader than any other existing place. The LUNA ecosystem

aims to create a network of scientists, trainers, investors, managers, students, researchers, and entrepreneurs who are connected to ESA-DLR facilities and contribute to expanding and sharing knowledge on lunar activities.

This indoor facility enables new investigations concerning human and robotic missions, also understanding how human and robots can cooperate to achieve mission success when flying on the lunar surface. As symbolized by its logo depicted in Fig. 2, LUNA is a terrestrial facility that will allow the preparation for the next Moon mission aimed at stepping stone for the ultimate destination, Mars.



Fig. 2 LUNA logo (credit: ESA/DLR)

2.1 LUNA main features

The LUNA training and technology centre is composed by the main hall, a standard industrial building outfitted with special systems, to which several external elements are attached. From the initial concepts dated back to 205, the ESA-DLR LUNA analog facility was officially inaugurated on 25th September 2024 [8] as shown in Fig. 3.



Fig. 3 Opening of the LUNA facility on 25th September 2024 (from left): ESA astronaut Dr. Alexander Gerst, Mona Neubaur (Minister for Economic Affairs and Climate Protection in North Rhine-Westphalia), Dr. Anna Christmann MdB (Federal Government Coordinator for German Aerospace), Prof. Dr.-Ing. Anke Kaysser-Pyzalla (Chair of the DLR Executive Board), Josef Aschbacher (ESA Director General), and Daniel Neuenschwander (ESA Director for Astronautical and Robotic Exploration)

LUNA was specifically designed to replicate the key aspects of the harsh lunar environment such as dusty terrain, hypo-gravity, and lighting conditions.

The main feature of LUNA is a 700 m² regolith testbed area: it is completely covered and filled by almost 800 t of a specific regolith mare simulant named EAC-1 [9]. In addition to loose regolith, rocks and boulders are strategically placed on the simulated surface to enhance the lunar environment, providing an accurate replication of specific lunar

surface locations. Permanently installed seismic and other sensors are available to provide reference data for experiments. The dimensions of the regolith test field are approximately 33 m by 20 m, with a regolith depth of 60 cm, except for the deep floor area that has a depth of 3 m (with dimensions of 10 m by 14 m) and contains an artificial lava tunnel at its bottom. Various targets are embedded in the regolith layer to simulate different structures relevant to In Situ Resource Utilization (ISRU) techniques: in fact, these targets can be used for the application and verification of various geophysical methods for subsurface imaging. The Deep Floor Area can facilitate testing of sampling, excavation, and drilling activities. Depending on the type of test being conducted, the terrain can be shaped to resemble different topographic features present on the Moon. An adjustable ramp is also scheduled for installation at the beginning of 2026 to allow the replica of different terrain slopes ranging between 0 and 50 degrees of inclination; rovers and astronauts will thus be able to perform activities in or near craters and on non-flat terrains.

A dedicated dust chamber has also been built to allow for extreme dust exposure and testing of equipment under ambient environmental conditions. It contains 20 t of anorthositic type material originating in Greenland [10] has a floorspace of approximately 4 by 4 m. To complement and study the full lifecycle of the lunar resources extracted in-situ, a fully equipped gas laboratory will also be built in LUNA by the end of 2026.

LUNA will provide simulations of lunar Extravehicular Activities (EVAs) with a system capable of simulating reduced gravity operations with high fidelity. Within this framework, a system named PUPPETEER will offer multi-agent, gravity-offloading capabilities for astronauts and other payloads such as rovers and lander mock-ups within the regolith testbed area [11]. To achieve these functions, a ceiling-mounted omnidirectional vehicle-based approach is proposed. Each vehicle utilizes a patented locomotion system that allows multiple independent vehicles to operate over a ceiling structure with omnidirectional mobility, ensuring maximum mobility for each individual payload. The gravity-offloading function is achieved by equipping each vehicle with an adjustable semi-passive spring mechanism based on the constant-force energy storage principle [11]. A suspension cable connects the offloaded payload to its dedicated vehicle. The PUPPETEER system provides each payload with access to a significantly expanded operational workspace, surpassing the capabilities of conventional gantry crane solutions, and offers a high-fidelity reduced gravity solution for LUNA. This system aims to train astronauts and flight control personnel for lunar surface operations and EVAs, and enables researchers and engineers to develop and test upstream systems for lunar exploration. The development of the PUPPETEER system began in early 2024, with plans to be fully operational by Q2 2026.

Unlike the Apollo era, current exploration focuses on lunar poles, as outlined in NASA's Artemis plans [5]. Local topography combined with low Sun angles creates unique conditions like bright areas next to permanently shadowed regions [12], [13], [14]. To accurately replicate challenging conditions, where brightly lit spots are adjacent to very dark shadowed areas, a dedicated Sun simulator will be built and installed in LUNA. This movable system will be adjustable to match specific lunar latitudes and Sun positions. Sensors, cameras, robotic systems, and EVA protocols will be tested and validated against realistic light conditions. To accommodate early test, initial spotlights have been installed and complement the portfolio of the equipment available in LUNA.

To further immerse users in a realistic Moon landscape, LUNA will use Virtual Reality (VR) and Mixed Reality (MR). With EAC's proximity and their XR Lab experts, LUNA will integrate VR and MR goggles into simulation protocols. This will make LUNA one of the largest eXtended Reality (XR) areas worldwide. Tracking and haptic devices, like force feedback, will allow real and virtual objects to appear simultaneously, enhancing analogue activity simulations. This will complement the research capabilities in low gravity environments and enhance the preparation for parabolic flight test campaigns for lunar XR applications [15].

To connect all the different systems and to create a proper lunar framework, an initial LUNA Ground segment [16] has been established. Its activities will range from monitoring and controlling of experiments up to enabling communication with astronauts during the execution of EVAs. Starting from the existing International Space Station (ISS) ground segment infrastructure, new paradigms and standard are nowadays developed by DLR and ESA experts. The remote connection with other ISS control centres and the establishment of new control rooms from other distant location to operate the LUNA facility and its different elements, will help in the creation of novel standards required for Gateway and surface operations with the international partners in the framework of the Human Exploration Control Centre capabilities [16], [17], [18]. The Monitoring and Control System of LUNA (MCS-L) provides a variety of tools to display and command user's experiment. A dedicated the LUNA Disruption Tolerant Networking (DTN) is also currently being developed to increase the realism of the simulations with command and communication delays.

An overview of the LUNA main testbed is represented in Fig. 4.

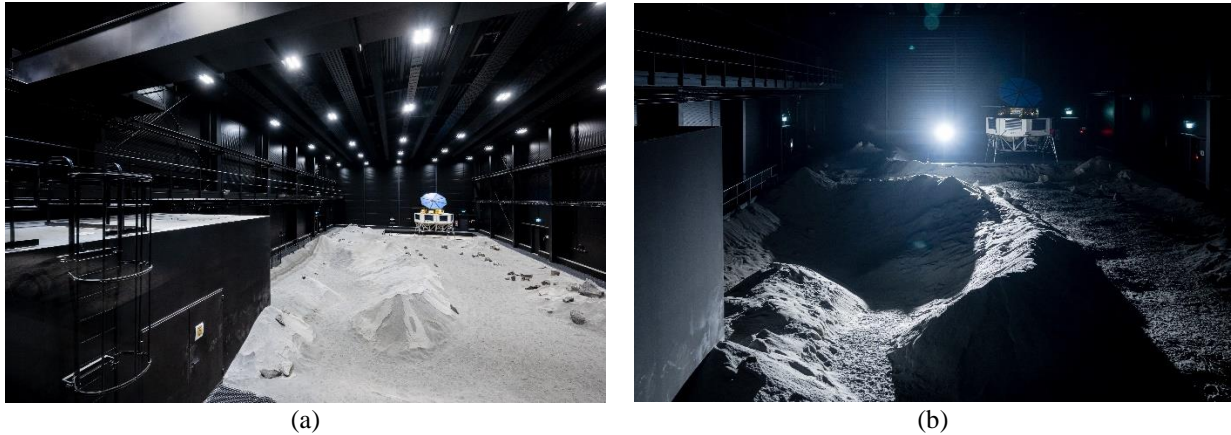


Fig. 4 Overview of the LUNA regolith testbed area featuring the deep floor area, geological sample and the ESA Argonaut lander mockup depicted with ambient light conditions (a) and with the provisional sun simulator light turned on (b) (credit: ESA/DLR)

2.2 External connections

To complement to spectrum of activities and allow for end-to-end multi-days mission simulations, the main LUNA hall will be connected to external modules.

A key element for enabling long-duration missions on the lunar surface is a pressurised habitat where humans can safely live and conduct scientific experiments. To address this need and to investigate how such habitat can function, the Future Lunar EXploration Habitat (FLEXHab) module [19] was delivered and installed in March 2025. Thanks to its connection with the regolith testbed area through a dedicated hatch, astronauts can carry out egress and ingress protocols for surface EVAs. The habitat's internal flexibility allows it to be repurposed based on the requirements of different analogue campaigns. Surface experiments can be monitored from FLEXHab, and various payloads can be accommodated inside to research different aspects of lunar science, such as geology and material science.

Furthermore, to enhance the capacity for investigating aspects related to human physiology and psychology within the LUNA framework, research will be conducted at the DLR :envihab facility [20]. Utilizing this DLR facility for complete isolation will assist scientists and medical professionals in understanding how to adapt mission protocols to manage life during future lunar missions, thus having :envihab serving both as complementary research facility or as additional crew quarter.

Another external LUNA element is the EDEN LUNA greenhouse, a facility originally tested in Antarctica [21]: The greenhouse will be equipped with a robotic arm for automated gardening and harvesting, focusing on research into plant cultivation in a controlled lunar environment. This facility will advance biological research and explore interactions between astronauts and their environment during long-duration missions [6].

Additionally, LUNA will feature an extra container, equipped for sunlight, microwave, and laser regolith sintering. This capability is important for developing techniques to utilize lunar materials for construction and other purposes, advancing ISRU.

3. Initial test campaigns

Despite being recently open and not fully completed, LUNA already successfully hosted few test campaigns that served as validation for the operational processes and the functionalities of certain elements. The primary objective was to evaluate the mobility and remote controllability of the rovers within a realistic lunar environment (as shown in Fig. 5).



Fig. 5 Commercial of the shelf rover driving in LUNA (credit: ESA-DLR)

For certain test, attention has been given to the rover payload, such as ground-penetrating radars. There has been interest also in testing geophones, various seismic measurement methods, and a swarm surface navigation system.

LUNA served also as validating platform for a mission already flying towards the Moon: in fact, the Resilience lander, launched in January 2025 and operated by the Japanese company iSpace, is currently scheduled to land in June 2025 in Mare Frigoris. The lander carries a small Luxembourg-built rover called Tenacious and the iSpace team tested the rover in LUNA to fine-tune the payload deploying mechanism, to train the ground segment operator and to check the mobility and driving mechanisms [22].

Other initial tests were conducted to simulate EVAs with dedicated analog suits named ExCon from Atlas Devices LLC [23].

4. Conclusions and future outlook

Humankind is preparing to return to the lunar surface, aiming to establish a permanent human presence. With current technology advancements and experience from past endeavors, humanity will be able to prepare for landing on Mars. Achieving this objective requires new facilities to develop and test technologies and train astronauts.

This paper describes the ESA-DLR LUNA analog facility, its current status, and initial test campaigns conducted. This training and technology centre offers an accessible entry point for various actors involved in lunar science, facilitating tests and validations, ranging from end-to-end simulations of lunar surface missions to components testing. Located on the DLR Cologne-Porz campus near EAC, LUNA replicates essential lunar environmental conditions such as dust, reduced gravity, and illumination. LUNA is available not only to spaceflight experts but also to research centres, academia, private companies, and start-ups. It helps to integrate novel terrestrial technologies and transition space-rated technologies. Sharing knowledge and lessons learned with the Moon research community is a key goal of LUNA. Through fostering international cooperation, Europe is positioning itself as a hub for Moon-related research and initiatives.

LUNA facility was officially inaugurated in September 2024: its commissioning and utilization already started with the first test campaigns. The completion of the facility is expected by the end of 2026.

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