



EXPLORATION SCIENCE AT THE MOON

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1. INTRODUCTION

ESA's strategy for human and robotic space exploration, Explore2040, defines the approach and priorities for exploration of Low Earth Orbit, the Moon and Mars. This strategy sets out, among others, a goal to allow Europeans to explore the Moon, to contribute to unveiling the mysteries of the Solar System's formation, and to trigger technological innovation in preparation for the human journey to Mars.

Science is fundamental to achieving this goal. ESA's lunar exploration missions and platforms provide unique opportunities for world-class research in human health, life sciences, physical science, space science, planetary science, astronomy and astrophysics. Major scientific projects will be major users of the capabilities and infrastructure that will be built up at the Moon in the coming decades. At the same time, dedicated research is essential to establish new knowledge that is needed to address the challenges of robotic and human exploration.

Two complementary science streams are defined in Explore2040:

- **Exploration-enabled science:** science that becomes possible because exploration takes place. This includes curiosity-driven and applied research selected through competitive Announcements of Opportunity on the basis of scientific excellence.
- **Exploration-focused science:** science driven by programmatic needs and closely linked with technology de-risking. This is the science that must be carried out in order to enable and safely conduct exploration activities.

Within exploration-focused science the following themes have been identified, and are discussed further in the following sections in the context of exploration of the Moon:

- Local resources,
- Environments and effects,
- Crew health and performance,
- Habitation.

For exploration-enabled science, themes include basic and applied physics, biology and human physiology, and planetary sciences. Enabled science is driven bottom up by the priorities of the scientific community.

This document describes the areas where ESA is focusing efforts and resources for scientific activities at the Moon and in support of lunar exploration. The purpose of this document is to provide direction for the definition, proposal, selection and implementation of new lunar science activities within ESA's Terrae Novae Exploration programme. Crew health and performance related research is excluded from this document.

Three key tenets regarding the future of lunar exploration are considered as key in defining priorities for focused science activities. These tenets are fundamental assumptions regarding the future direction of lunar exploration, regardless of any given specific mission, architecture or programmatic framework. For any implementation scenario these aspects will remain valid.

Tenet 1: Operational risk and safety related to environmental hazards are major factors driving locations and capabilities for robotic and human missions and infrastructure

It is essential to identify and characterise potential hazards related to the lunar environment and the conditions there, to establish models that allow these conditions and their effects to be predicted and to support the establishment of mitigation approaches.

Tenet 2: Lunar resources are unlikely to be used before 2040, but proximity to promising strategic resources will drive where infrastructure like a Moon base will go.

It is essential to establish which lunar resources are promising for the future, where these resources are, their extents and physical properties. This information will become a driver for where we explore and which capabilities we establish to explore there.

Tenet 3: “Big Science” use cases will become the drivers of a Moon base and other lunar infrastructure in the next decades.

While the rationales for undertaking human and robotic exploration, including the establishment of a Moon base or other infrastructure are not purely scientific, the detailed definition of what

they need to do will be driven by science use cases. Facilities for geosciences research, astrophysics, cosmology, fundamental physics and other large scale scientific endeavours will become drivers for functionality and will be what this infrastructure is used for first and foremost. We can prepare the way for these future scientific facilities by characterising the suitability of the lunar environment and developing the scientific instrumentation and methods that will be needed in the future.

2. IMPLEMENTATION OPPORTUNITIES FOR LUNAR SCIENCE

The ESA Terrae Novae programme provides a means to undertake scientific activities in support of and enabled by Moon exploration, both at the Moon and using ground-based facilities on Earth.

Means of accessing the Moon, undertaking investigations there and gathering scientific data include:

- Surface missions enabled by ESA's Argonaut lunar lander
- Small Missions, which are developed rapidly within the ESA programme
- Scientific instruments and suites of instrument flown with international partner and commercial missions
- Commercial data purchases from privately conducted missions
- Analysis of returned samples received through international partnerships
- Data sharing with international partners
- Establishment and use of a reference system for time and positioning on the Moon

In addition, ground-based facilities can be accessed and used to support ESA's research needs for lunar exploration. Such facilities include:

- Diverse terrestrial laboratories
- Lunar simulants and terrestrial analogues
- Lunar environment analogues
- Partial gravity parabolic flights.

Research undertaken using these platforms and facilities should address ESA's focussed science themes, whilst also enabling fundamental scientific research.

3. EXPLORATION FOCUSED SCIENCE THEMES

The following section describes the primary exploration focused science themes to be addressed by ESA's research at the Moon. In each case the premise for the activities is set out, goals are described and the derived data products of interest are summarised.

It is noteworthy that substantial overlap exists between application driven focused science and more fundamental enabled science. Undertaking focused science research will result in new enabled science. Focussed science is a priority, given the importance of preparing and derisking missions and capabilities which will enable science in the future.

This document therefore emphasises exploration “focused science” as the near-term driver of activities, noting that exploration “enabled science” comes as a secondary outcome of most focused science activities.

3.1. Environments and Effects

The Moon has a complex, dynamic and fragile environment. This environment offers insights into the physics of how airless bodies interact with their parent stars, the interplanetary environment and cosmic radiation. It is also an environment in which humans and robotic systems must learn to live and operate. Importantly, the lunar environment will be permanently changed by human activity, and these changes must be monitored and understood.

In addition, future missions require safe landing, reliable operations and access to scientifically valuable locations. Identification and characterisation of hazards, environments and surface properties are essential.

Goals within this theme are:

- Characterise and understand the lunar environment and how it works and evolves.
- Understand how the environment affects people, biology and technologies to inform the design, build and operation of lunar missions and infrastructure.
- Understand and monitor how human activity is changing the lunar environment
- Characterise hazards at candidate locations for future missions and infrastructure

- Develop maps and models supporting mission preparation

The environment can be described and understood in terms of its topographic properties and the dynamics of conditions there. Relevant physical and topographic properties of specific location, include rocks, craters, slopes, shadowing and other topographic hazards. Dynamic conditions are driven by the coupling of multiple physical phenomena which together can be hazardous to exploration activity. Aspects to be considered include; radiation, electrical charging, impacts, dust, and seismic activity. These phenomena can vary both temporally and spatially. Measurements are therefore ultimately needed across a prolonged timeframe and at different spatial scales. The understanding of this environment and a practical application of this understanding will be achieved through a combination of theoretical prediction and measurements, leading to the production of integrated models of the environment and its effects.

Tables 1 and 2 summarise data sets that need to be generated and the way in which they are important to support exploration needs.

Table 1: Environment data sets and research

Derived Data Product	Exploration Application
Plasma properties	Understanding and monitoring of how solar wind and magnetospheric plasmas interacting with the surface lead to charging of equipment and the lunar surface itself.
Charging and potential differences	Determining the potentially hazardous charging of equipment, regolith and materials and how this is affected by illumination, charged particles and triboelectric effects.
Magnetic fields	Plasma measurements must be referenced to local magnetic fields, which strongly affect their behaviour.
Energetic particles	Characterising galactic cosmic rays and solar energetic particles and the secondary radiation populations they generate as hazards for crew and electronics.
Dust and particulate mobilisation	Understanding and constraining dust mobilisation caused by electrostatic effects, meteoroid impacts and human activity as a potential hazard.
Dust adhesion	Dust adhering to equipment creates operational hazards; mechanisms for dust adhesion are poorly characterised and need to be refined.
Neutral exosphere	The tenuous lunar atmosphere will be rapidly altered by human activity. Whilst arguably an enabled science topic, measurements to characterise this aspect of the environment are time critical.
Seismic environment	Understanding moonquakes, as a potential risk is important for long-duration infrastructure design and stability.
Impact fluxes and effects	Impacts by meteoroids of various sizes and secondary particles are a hazard, in particular for large equipment and long lived items.
Biological responses	Understanding biological responses to radiation, partial gravity and lunar dust informs crew health risk assessments, countermeasures and habitation limits.

Table 2: Data sets and research for landing site and exploration zone characterisation

Derived Data Product	Exploration Application
High-resolution digital terrain models	Needed for determination of landing site safety and traverse planning.
Regolith geotechnical properties	Enables the preparation of operations and of surface technologies and systems for applications including: mobility, drilling, excavation, and regolith handling and processing.
Regolith disturbance	Assessment of hazards created by rocket plumes excavating, projecting and altering the regolith.
Terrain intelligence maps	The integration of different data to provide specific tools for operational planning (e.g. illumination predictions for polar regions)
Images	Provide contextual and operational insights.

3.2. Local Resources

The Moon has resources including water ice, oxygen, volatiles, metals, rare earth elements and building materials. These resources may or may not ever be considered reserves. They might not be useful. We might or might not ever use them. These uncertainties exist because significant knowledge gaps remain regarding their abundance, distribution, chemical and mineralogical context, physical properties, and the local conditions where they are found. These resources are distributed across the surface and subsurface and reflect the complex geological history of the Moon. Only by understanding the nature of these resources can we determine their future potential and how that might drive the future of lunar exploration.

Goals include:

- Determine the composition, abundance and distribution of water ice and mineral resources (e.g. metals) to determine their potential for future use.
- Understand the processes that led to the concentration and redistribution of these resources.
- Characterise the geotechnical and environmental conditions in which resources are found.
- Establish the scientific basis for extraction and utilisation processes.

When and if local lunar resources will be used will depend on their abundance, distribution and physical properties. These factors will determine whether these resources might at some point be considered as reserves. In any case it is likely that access to promising resources and the ability to process them will be an important factor in planning future missions and infrastructure in terms of location and technical capabilities for mobility, measurement, extraction and processing. It is therefore important to establish a comprehensive understanding of resources of interest. Such knowledge will also underpin aspects related to governance of these resources and related lunar activities.

For example, water ice as a resource has become a major driver for lunar activity. Multiple missions target the lunar South Pole, which is also considered as location for infrastructure to be established. However, while polar water ice is known to be present, its potential for practical use remains undemonstrated. It is important therefore to both properly characterise potential water ice reserves, and to explore potential reserves of other resources, which may be located away from the poles. In all cases resource maps, need to be generated. These maps represent a model of the resources and their properties, such that their practical and economic utility can be assessed.

Table 3 describes the derived data products to be generated for exploration of lunar resources.

Table 3: Local Resources data and research

Derived Data Product	Exploration Application
High-resolution geological maps	Such maps provide the basis for surface mission planning, site selection, sampling strategies and resource exploration.
Water ice and volatile distribution maps	Such maps provide the basis for assessments of the potential of water ice and other volatile based resource utilisation, at the poles or elsewhere.
Mineral and metal resource distribution maps	Such maps provide the basis for assessments of the potential of resource utilisation through metal and oxygen extraction from lunar minerals. Priorities shall be given to potential sources of titanium, rare earth elements and platinum group metal resources.
Regolith geotechnical properties	Required as data to support any resource-based activity requiring traverses or the excavation and processing of regolith.
Resource extraction and processing process data	Chemical and physical processes underpin in situ resource utilisation and need to be understood and advanced (e.g. reduction, beneficiation, purification).

3.3. Preparing Long-Term Enabled Science

The Moon will become a platform for world-class science that cannot be performed on Earth. Examples include radio astronomy on the far side and gravitational wave observatories. Human and robotic field geology will provide new sample collections revealing the evolution of planetary bodies and the Earth–Moon system. These and other scientific applications will require dedicated facilities, infrastructure and comprehensive knowledge of the environments in which they operate. Preparing longer term capabilities for enabled science should start now. Focused science now prepares the basis for the highest possible impact science in the longer term.

Scientific use cases are likely to demand:

- Long distance mobility with in situ analysis, sample retrieval and sample return for geosciences, including both resources mapping and fundamental geology.
- Long duration environmental and geophysical stations with a regional and global distribution for environmental studies, geophysics, fundamental physics; both focussed and enabled science.

- Pressurised environments with laboratory facilities and sample return for life sciences applied to crew health and performance, habitation studies and more fundamental astrobiology.
- Modular and scaleable arrays of far-side radio antenna arrays for astronomy, astrophysics and cosmology.
- Long and stable baselines for astronomical telescopes and laser interferometers for astronomy, astrophysics and gravitational wave observations.

Goals include:

- Determine suitability of the Moon for gravitational wave observation
- Maintain European leadership and capabilities in lunar geology and sample science
- Assess feasibility of lunar far-side radio astronomy in the lunar environment
- Prepare the scientific instrumentation and methods needed for the future
- Enable early fundamental science alongside focused science activities