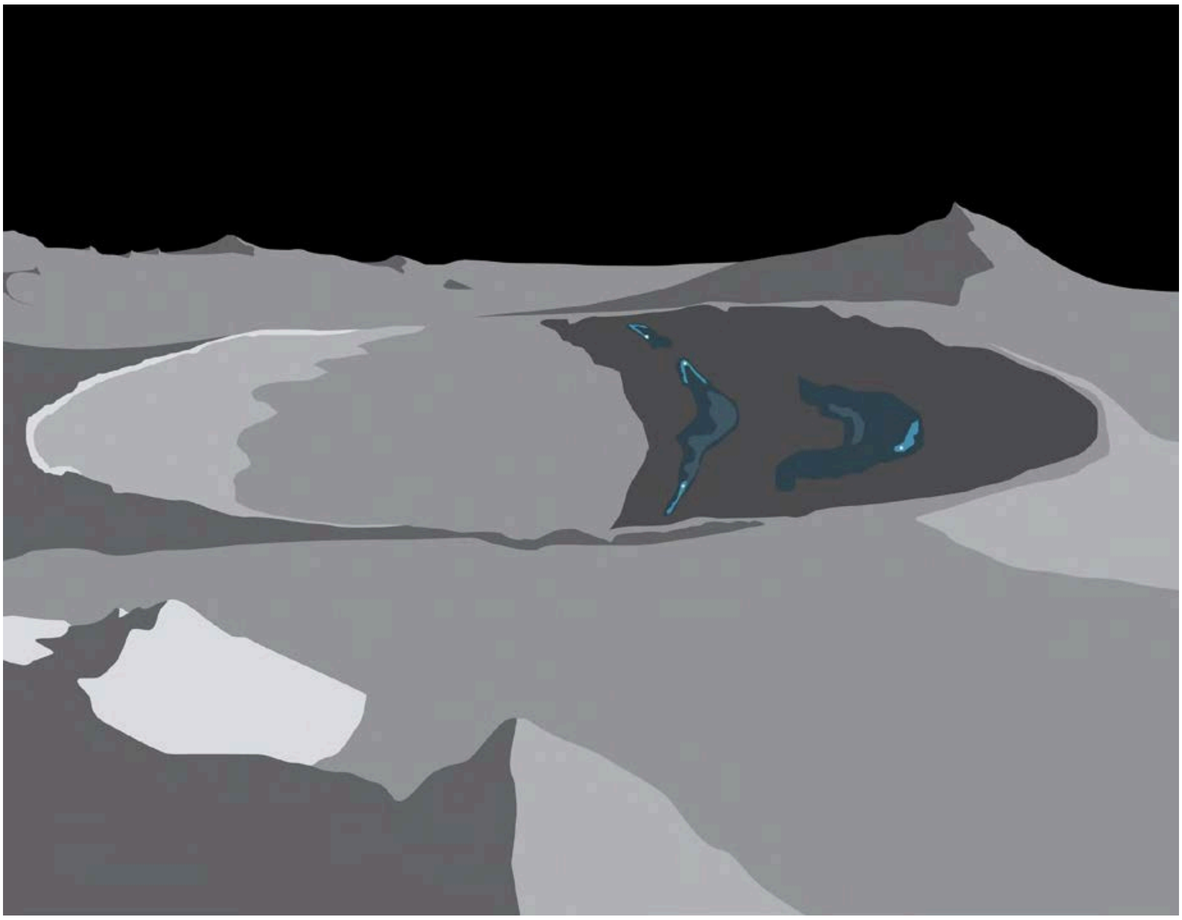
ESA Strategy for Science at the Moon



European Space Agency
Agence spatiale européenne

EXECUTIVE SUMMARY

A new era of space exploration is beginning, with multiple international and private sector actors engaged and with the Moon as its cornerstone. This renaissance in lunar exploration will offer new opportunities for science across a multitude of disciplines from planetary geology to astronomy and astrobiology whilst preparing the knowledge humanity will need to explore further into the Solar System. Recent missions and new analyses of samples retrieved during Apollo have transformed our understanding of the Moon and the science that can be performed there. We now understand the scientific importance of further exploration of the Moon to understand the origins and evolution of Earth and the cosmic context of life's emergence on Earth and our future in space.

ESA's priorities for scientific activities at the Moon in the next ten years are:

- Analysis of new and diverse samples from the Moon.
- Detection and characterisation of polar water ice and other lunar volatiles.
- Deployment of geophysical instruments and the build up a global geophysical network.
- Identification and characterisation of potential resources for future exploration.
- Deployment long wavelength radio astronomy receivers on the lunar far side.
- Characterisation of the dynamic dust, charge and plasma environment.
- Characterisation of biological sensitivity to the lunar environment.

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1 INTRODUCTION

The Moon is a unique scientific resource, just three days from Earth, and whose true potential is only just being realised. The Moon is an archive of Solar System and cosmic history. The Moon preserves a record of the Earth-Moon system's formation and the context for the emergence of life on Earth. The Moon provides a reference point for planetary science across the Solar System. The Moon may provide resources for future space exploration missions and to expand a space economy. The Moon provides a platform from which we can observe our Universe as never before. Recent scientific results have shown that we have only just begun to understand science of, on, and from the Moon and that there is a scientific imperative to return.

This document summarises a strategy for science at the Moon that takes advantage of mission opportunities starting in the early 2020s and prepares for comprehensive scientific activities on European-directed missions. Activities include:

- Creating early and regular flight opportunities for payloads to the Moon.
- Rapid development of high readiness payloads for missions of opportunity.
- Definition and development of payloads for directed missions targeting strategic science.
- Supporting science ground segments and operations.
- Providing European scientists with access to new lunar samples and ensuring the capability to deliver sample science.
- Building and supporting the community of European scientific users and international scientific collaboration, cooperation, and coordination at the Moon.

These activities enable the scientific community to address high priority science and to prepare strong European scientific contributions toward the human and robotic missions that are to come.

2 OBJECTIVES

A science strategy shall be implemented to achieve the following objectives:

- Create new opportunities for the European scientific community to deliver payloads to the Moon and access lunar samples to perform world class science.
- Develop and maintain research capabilities, instruments, payloads and enabling technologies that can be used by the European science community to deliver world class science both at the Moon and with returned samples on Earth.
- Generate new knowledge that prepares for future exploration activities.
- Grow and strengthen the scientific community to prepare strong European science participation in future exploration missions.

- Deliver access to the Moon for science in ways that contribute to the competitiveness and growth of European industry.
- Support new and existing international cooperations.
- Inform and inspire the public, improving public perceptions of science and exploration, and supporting the establishment of the future scientific and engineering workforce.

3 INTERNATIONAL AND SCIENTIFIC CONTEXT

Recent international missions to the Moon and new analyses of Apollo lunar samples have transformed our understanding of the Moon and its future role as a platform for scientific research. Remote sensing missions with European instrumentation and scientific involvement have provided a global view and a new context for the in situ and sample measurements of the past. Meanwhile a robotic return to the surface has been initiated by China, with European scientific involvement and instrumentation. New analyses of Apollo samples using modern techniques and instruments have also profoundly affected our assessment of the Moon and its history, with around 38% of all lunar sample research being conducted in Europe.

This is the beginning of a new era of lunar exploration. The 2020s are likely to see a host of new missions to the Moon. The year 2019 has already seen the first landing at the lunar far side by China, and will also witness the first private sector lunar missions, India's first lunar lander, and the first lunar sample return mission since the 1970s by China. In the early 2020s NASA plans to support regular commercial flights to the lunar surface for payloads through its Commercial Lunar Payload Services (CLPS) programme, whilst preparing mid and large landers to prepare for new human missions to the surface. Additional missions are also planned in the early 2020s by China, Japan, and South Korea. The Global Exploration Roadmap foresees these early missions as preparation for sustained, international human activity on the Moon from the 2030s, offering unprecedented opportunities for science.

4 SCIENCE AT THE MOON

Scientific research opportunities at the Moon are hugely cross disciplinary covering planetary and space sciences, life sciences, physical sciences and astronomy. Scientific areas that can be addressed and the priorities of the science community have been identified and published on a number of occasions [e.g. RD1, RD2]. A consolidated European summary of these collective science cases was prepared in 2012 [RD3]. Additions and updates to these science cases due to recent scientific results are noted in Annex 1. Key changes concern the complexity and diversity of the early geological activity, the abundance and opportunities of cold trapped lunar ice, and the possibility that the Moon continued to be geologically active for far longer than previously thought. Some of the key properties of the Moon that give rise to its scientific value are summarised in
Table *1*, also noting that the close proximity of the Moon makes it uniquely accessible as a planetary body for research.

A convention among the scientific community is to describe scientific research at the Moon in terms of:

- **Science of the Moon**, where scientific investigations explore the formation, history and evolution of the Moon.
- **Science on the Moon**, where scientific investigations utilise the unique properties and environment at the lunar surface as a facility for conducting scientific research.
- **Science from the Moon**, where scientific investigations utilise the unique properties and environment at the lunar surface as a platform for astronomical observations.

These three science areas are summarised in *Table 2* and are described in detail in RD3 and Annex 1. The science areas can also be considered in terms of scientific themes which have been identified by the science community and recorded in the International Space Exploration Coordination Group's (ISECG) Science White Paper titled, 'Scientific Opportunities Enabled By Human Exploration Beyond Low-Earth Orbit' [RD4 and Annex 3].

Property	**Scientific Importance**
Reference planetary body	The benchmark for how planetary bodies are formed and evolve
Common origin with Earth	Key to understanding the origin of Earth and Moon
Ancient surface	A unique witness plate to Earth's early history and the history of the Solar System
No atmosphere	Reference point for space-surface interactions and physics
Cold trapped volatiles including ice	A record of life-enabling chemistry in the Solar System
Radio quiet	Unique platform for astronomy
A source of resources	Materials on the Moon can be a source of water, propellant, metals, oxygen, which are key for sustainable exploration
Lunar surface environment	Natural laboratory for testing the impact of hypogravity and radiation on biological models in preparation for future long duration exploration

Table 1 - Summary of some of the key properties of the Moon and their relevance for the Moon as a destination for scientific research.

Of the Moon	**On the Moon**	**From the Moon**
Bombardment	Habitability of the Earth through time	Radio astronomy
Structure from core to crust	Life in the Universe	Optical and infrared astronomy
Rock diversity and distribution	Survivability in space	Cosmic ray astronomy
Polar volatiles (e.g. ice)	Physiology and medicine	
Volcanism	Fundamental physics	
Impact processes	Space physics	
Regolith	History of the Sun and Solar System	
Atmosphere, plasma and dust	Impact rate	
Tectonics	Earth-Moon formation	

Table 2 - Science of the Moon, on the Moon, from the Moon as identified by the global scientific community and described in detail in RD3 and Annex 1.

5 SCIENTIFIC ACTIVITY PRIORITIES TO 2030

A set of scientific activity priorities for the 2020s have been defined with the support of an interdisciplinary scientific team [Annex 2] and are described below (in no particular order). These priorities should be supported wherever possible by new remote sensing data sets to inform targeted surface exploration. ESA activities should address or contribute to these objectives.

Analyse new and diverse samples from the Moon. New lunar samples are needed. These should be from diverse lithologies, including mare basalts, especially those that appear 'young' based on crater counts, samples associated with surfaces of different ages including the oldest impact basins, and plutonic samples (e.g. Mg suite). Dating these samples and analysing their composition and mineralogy will:

- better constrain the cratering rate throughout Solar System history
- test the global distribution of the Lunar Magma Ocean
- test the global distribution of volatile loss and isotopic fractionation
- inform models of lunar mantle evolution
- assist in the interpretation of palaeoregoliths found trapped between basalts

[see also RD5, RD6].

Detection and characterisation of polar water ice and other lunar volatiles. Measurements are needed within Permanently Shadowed Regions and areas with exposure to the Sun at high latitudes to determine the physical and chemical state of water, its concentration, and its vertical distribution. Detection and characterisation of other lunar volatiles and organics should also be conducted, with special attention to be paid to the possible cosmic ray induced synthesis of organic molecules of astrobiological relevance. The properties and sources of lunar volatiles in non-polar locations should also be determined.

Deploy geophysical instruments and build up a global geophysics network. Deployment of such instrumentation and an eventual network would constrain models of the lunar interior and address questions on present day seismic activity. Both seismic and heat-flow measurements are required with global coverage. Laser retroreflectors are required at new locations at the surface.

Identification and characterisation of potential resources for future exploration. Providing detailed lateral and depth-related characterisation of the chemical, elemental, and physical properties of potential sources of oxygen, propellant, life support consumables, and metals. Targets should include cold trapped polar ice, pyroclastic deposits, and high-titanium regolith.

Deploy long wavelength radio astronomy receivers on the lunar far side. This would test and demonstrate the unique suitability of the lunar environment for cosmic dark ages astronomy, to be followed by the first measurements of the cosmologically important red shifted Hydrogen I line. This would feed forwards to the first interferometer through a network of antennae.

Characterise the dynamic dust, charge and plasma environment. This takes advantage of the Moon as a physics test bed for the interactions between an airless planetary body and a parent star. It also determines the environments of future long duration surface missions. This requires the measurement of the interactions between the dusty surface of an airless body, its exosphere, solar radiation, and plasma and magnetic fields from the Sun and the Earth’s magnetosphere.

Characterisation of biological sensitivity to the lunar environment. Measurement in situ or on return to Earth of the impact of the lunar surface environment on a representative biological model. Determination of a valid biological model in addition to the optimal metric(s) and biomarker(s) that reflects the impact of the radiation and/or hypogravity environment at the lunar surface is required.

6 STRATEGIC OUTCOMES BY 2030

Activities implemented during the period 2020-2030 should deliver as a minimum the below listed outcomes to address the above priorities. These outcomes are to be achieved utilising European instrumentation, ideally as part of internationally coordinated activities accompanied by new orbital data to optimise the overall science return.

- New lunar samples returned from a minimum of two unexplored locations with subsequent analysis in European laboratories.
- In situ measurements conducted on polar water ice and other polar volatiles.
- A suite of measurements obtained from at least one geophysical package, ideally as part of a global lunar network.
- Geochemical, mineralogical, and geophysical measurements conducted on a non-polar resource deposit.
- In situ measurement attained of the dust, plasma and exosphere environment at the lunar surface.
- At least one new laser retroreflector deployed at the lunar surface.
- Measurement of the impact of the lunar surface environment on a representative biological model.

7 RESEARCH CAMPAIGNS

The above outcomes should be considered in the broader context of longer term research campaigns, implemented over multiple missions, through international coordination and with ever increasing scientific return. While each outcome contributes new and unique science the value is significantly enhanced if placed in the context of a broader and cumulative research effort, which contributes to one or more of the science topics introduced in Section 4 [see Annex 4].

These research campaigns begin with single opportunistic payloads on Missions of Opportunity producing early science results, which are built upon by later missions. These campaigns address globally recognised scientific challenges and so can also provide a framework around which international scientific coordination can be built. International cooperation and coordination is almost certainly required to optimise the science return and deliver the campaigns. The early phases of these campaigns should deliver scientific results whilst building the scientific community and the capabilities needed as the scientific capacity grows on robotic precursor missions, and eventually human missions.

The campaigns are summarised below and are described in more detail in Annex 5:

- **Campaign 1: Analysis of new lunar samples**. The accumulation and analysis of new samples from diverse locations across the Moon to establish a complete and integrated scientific picture of the Moon and inner Solar System history.
- **Campaign 2: Characterisation of cold trapped polar volatiles.** In situ measurements at the poles in different environments followed by comprehensive local mobile exploration at sites of highest scientific interest. Eventual sample return.
- **Campaign 3: Geophysical measurements of the lunar interior.** Deployment of a minimum of one geophysical station at the lunar surface with a goal of achieving several coordinated stations in diverse locations on the near and far side. Instruments include seismometers, heat flow probes and laser retroreflectors.

- **Campaign 4: Plasma, exosphere and dust environment and effects.** Deployment of a minimum of one environment monitoring station at the lunar surface with a goal of achieving several coordinated stations in diverse locations including the equatorial and polar regions. Instrumentation could include mass spectrometers, dust detectors, magnetometers and electric field sensors.
- **Campaign 5: Near surface geology, geophysics, mineralogy, and geochemistry.** Deliver geochemical instrumentation to the lunar surface to new sites [e.g. RD8]. Instrumentation of interest could include imaging systems (e.g. ground penetrating radar), instrumentation to measure elemental composition (e.g. x-ray and laser induced breakdown spectrometers) or mineralogy (e.g. infrared and Raman spectrometers).
- **Campaign 6: Biological and physiological effects of the lunar environment**. Measurement in situ or on return to Earth of the biological impact of the lunar environment associated with the lunar surface (e.g. radiation and gravitational) to inform human risk modelling and mitigation.
- **Campaign 7: Physics and astronomy from the Moon**. Deployment of laser retroreflectors to geographically dispersed locations at the surface of the Moon, deployment of a tripole radio antenna to the far side, and measurements of the natural dynamics of the dust environment in so far as it may affect future telescopes.

8 INTERNATIONAL COOPERATION

While individual missions and payloads can significantly advance scientific knowledge in a given area, comprehensive advancement in most identified areas of science at the Moon can only be achieved through coordinated activities at diverse locations. International coordination of science at the Moon is thus fundamental to achieving the goals of any of the described science campaigns.

Major areas for coordination include:

- Provision of payloads to international missions.
- Selection of landing sites to maximise overall scientific impact.
- Sharing access to data sets.
- Sharing access to new samples for analysis to optimise the capabilities of different laboratories worldwide.
- Facilitating scientific exchange on new results.
- Ensuring data sets from different missions in different locations are comparable through data standards, instrument performance standards, calibration standard, and common payloads.
- International engagement in science teams.

International coordination of scientific activities may be performed through bilateral agreements or through international forums including the International Space Exploration Coordination Group (ISECG). One approach could be the formation of an international lunar science and research team, perhaps within the context of ISECG. All of this is fully in line with the concept of a Moon Village.

9 MISSIONS

Two different classifications of missions are envisaged in the future ESA Exploration programme; Missions of Opportunity and Directed Missions.

Missions of Opportunity

Examples of missions of opportunity could include:

- An opportunity to provide a complete payload of up to 10 kg on a private lunar lander mission to a near side lunar location and to operate that payload for a given period of time, with a given allocation of power and data resources.
- An opportunity to contribute European elements to a payload that is led by an international partner and flown on that partner's mission to a lunar polar landing site. At the surface the payload is operated in line with the international partner's science operations plan. The contribution to the payload enables involvement in the science planning and operations, and preferential access to data for exploitation.
- An opportunity to access and perform research on a sample returned by an international partner's mission, which is enabled through an agreement between ESA and the international partner.
- An opportunity to have a cubesat, which performs stand-alone scientific operations, delivered into lunar orbit by a commercial supplier, who also provides a communications and operations support service.

Missions of opportunity will usually be realised through cooperative agreements between ESA and a partner.

Missions of Opportunity are likely to be characterised by:

- Rapid development and delivery requirements
- Severe resource limitations for power, data, mass and operations
- Increased risk compared with ESA driven mission procurements
- Lower cost to ESA than for Directed Missions
- Limited data return per mission

Directed Missions

Directed Missions are missions where ESA has defined a set of mission objectives and derives from these a set of mission and scientific requirements. There is then the basis for the procurement of a mission or flight opportunity that addresses those requirements. Directed Missions may be undertaken independently by ESA or may be defined and procured in cooperation with international partners.

Examples of a Directed Mission could include:

a) A mission (e.g. HERACLES) to demonstrate and mature technology for later human lunar surface missions, to perform preparatory mission operations, to perform scientific investigations at the lunar surface, and to return lunar samples. In such a mission ESA may contribute system elements to an overall international architecture and payloads to a payload suite with international contributions. The approach to sample receiving, curation, and distribution would be agreed and coordinated by the partner agencies in the mission. The mission's science planning and operations are managed cooperatively by the agencies involved and European scientists are assured access to both data and samples.

b) A mission in which ESA procures access to the lunar surface from a commercial mission supplier with the express purpose of deploying and operating a specific scientific payload at the lunar surface. The European science community is engaged in the definition of the mission and science requirements, supports science planning and operations, and accesses the data from the payload.

Directed Missions are likely to be characterised by:

- Technology and science driven mission definition, design and operations
- Increased ESA oversight of mission development and procurements within the constraints of the commercial mission capabilities
- Increased cost to ESA compared with Missions of Opportunity
- High scientific quality and high scientific return per mission
- Commercial procurement of mission services (e.g. access, communications operations)

Phases for scientific utilisation of the Moon

Scientific activity at the Moon's surface is envisaged in three phases of increasing extent and complexity through the 2020s as capacity, user community, and international cooperation in the area grow. The increase should be consistent with an evolving and growing programme of lunar exploration over the next decade. The phases are illustrated in
Figure **1** and are:

- Phase 1: Early science at the Moon on Missions of Opportunity.
- Phase 2: Science on Directed Robotic Precursor Missions with ongoing Missions of Opportunity.
- Phase 3: Science in Directed Human/Robotic Missions.

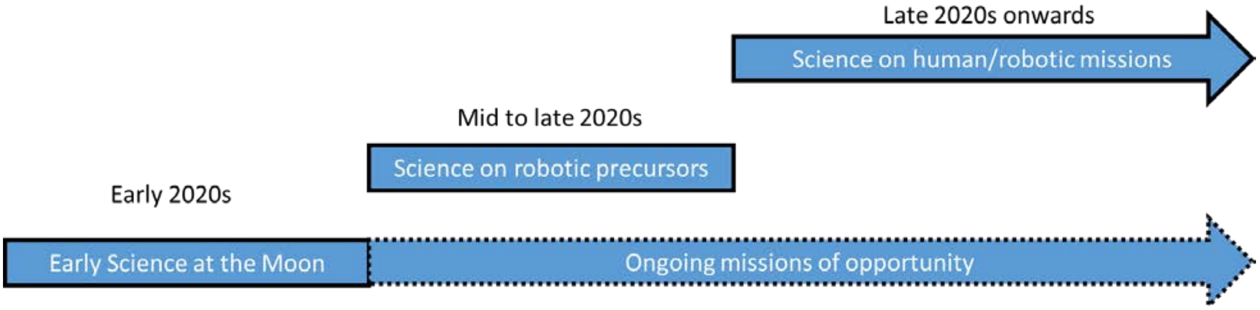

Figure 1 - Phases for scientific utilisation of the Moon

Phase 1: Early scientific utilisation of the Moon in the early 2020s. In Phase 1 individual payloads are delivered to the lunar surface and to lunar orbit on Missions of Opportunity, or scientific participation is made available in the missions of international partners. Payloads in Phase 1 will be selected based on their technical maturity, their technical and programmatic compatibility with the mission opportunities that exist, the costs associated with their preparation for flight, and the scientific impact they can be expected to deliver. Consideration will also be given to their function in initiating the activities of the scientific campaigns presented in Section 7 and their potential to contribute to preparations for future human exploration.

Phase 2: Robotic precursors in the mid to late 2020s. In Phase 2 scientific payloads should access the lunar surface on directed robotic precursor missions to future human exploration, and samples should be returned to Earth. These missions should be agency driven, meeting the scientific and technical requirements of the agency, implementing the scientific campaigns described in Section 7.

Phase 3: Human missions from the late 2020s onwards. In Phase 3 scientific activities at the lunar surface are performed as part of human surface missions. These activities will utilise comprehensive surface payload capabilities and sample return, also utilising orbital assets to address the scientific campaigns described in Section 7.

10 SCIENCE DEFINITION AND SELECTION

For Missions of Opportunity, science selection must be based on a bottom up assessment of what is feasible based on the availability of payloads for flight and mission opportunities. The scientific priorities and the progression of the campaigns will be used as guidelines for the science to be performed and a minimum threshold of scientific quality shall be assured by peer review. Where a need exists for scientific prioritisation for a given Mission of Opportunity, this should be based on an independent peer review in which the following are assessed:

- The likely scientific impact of a given payload on a given Mission of Opportunity.
- The scientific contribution of a given payload to the scientific priorities and the overall goals of a science campaign.
- The contribution of the measurements of a given payload to addressing unknowns of importance for future exploration missions [RD7].

For Directed Missions a top down approach to science selection is performed by ESA in consultation with the science community through dedicated mission science teams. Prioritisation of science on directed robotic precursor missions may be performed, noting that for robotic precursor missions the scope of the science that is possible will be determined by the capabilities and characteristics of a given mission, which are driven by exploration preparation objectives rather than science.

Science definition for a Directed Mission is therefore based on:

- Scientific feasibility within the scope and constraints of a given mission.
- Current priorities for contributions advancing one or more scientific campaigns.
- Contribution to addressing scientific challenges for future exploration missions.

11 PAYLOADS

Payload selection and development for Missions of Opportunity

For Missions of Opportunity payloads are accommodated on international or private sector partner led missions in an ad hoc manner in response to opportunities as they arise. These opportunities will differ in scope but are likely to require short development times. The approach to payload definition, selection, and development in these cases is conceived as a step-wise process[1].

Step 1: Issue a Request For Information. A Request For Information (RFI) will be issued to the science community on a bi-annual (TBC) basis or in response to specific new opportunities where needed. This RFI will be used to gather information on the availability and maturity of payloads that could be made ready in response to opportunities in the following 5 years, and which contribute to research campaigns addressing the scientific priorities. RFIs should present the Missions of Opportunity expected in that timeframe and the expected scope of environments and interfaces for payloads on these missions. The RFIs will be open to payloads that respond to these possibilities but would not be limited to these. The received payload submissions then constitute a pool of possible payloads that can be considered in determining the scope of instruments for selection.

Step 2: Assess feasibility and scientific priority. The submissions received in response to the RFI would then be assessed to ascertain likely feasibility for flight selection. Feasibility would be assessed based on:

- Heritage, Technology Readiness Level (TRL) and current level of maturity.
- Scientific relevance to one or more campaigns and science priorities.
- Development needs to achieve flight readiness.

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[1] This process was initiated, with a Request For Information in December 2018 *http://exploration.esa.int/moon/60923-request-for-information-lunar-exploration-campaign-science-and-technology-payloads/*. As of January 2019 the received submissions have been undergoing evaluation.

- Accommodation and interface requirements.
- Science team background and ability to support the payload and its science exploitation (including confirmed funding for data analysis).
- Effort required to achieve and maintain payload readiness.
- Budgetary constraints.
- Risks.

Scientific prioritisation shall be performed by a scientific peer review. Following review, the scope of science and potential payloads that could be considered for forthcoming missions of opportunity will be determined.

Step 3: Achieve and maintain an appropriate readiness level. A selection of payloads within the scope determined in Step 1 would then be matured to ensure compatibility with and readiness for the Missions of Opportunity. Payloads under development would constitute a pool from which selection for flight could be considered. Payloads need to achieve an appropriate readiness level and maintain that level of readiness in advance of a flight opportunity being confirmed. Payload activities will therefore be initiated for candidate payloads. Developments will consider the maturity of interface definitions and advance payloads to the extent that changes in interface and environment requirements can still be considered.

Step 4: Confirm opportunities and assign flights. Once a flight opportunity is confirmed, payloads are assigned to a flight, selected from the identified candidate payloads. Assignment to flight would follow a three stage process.

1) Candidate science payloads would be down selected for consideration for a flight based on technical compatibility, scientific performance, cost, risk and programmatic priorities.
2) Down selected payloads would then be considered along-side space resource and technology payloads, with a selection made through a process to be defined by May 2019.
3) The selected payload would then be procured.

Payload definition and development for ESA directed missions

New payloads for ESA directed missions will be selected and developed through a process driven by the scientific requirements of a mission. A series of steps for selection are envisaged.

Step 1: Define science objectives and establish scientific requirements. Scientific objectives and requirements shall be established through consultation with the science community through existing science teams (e.g. Topical Teams) or through ad hoc teams created to advise on a particular study or mission. The objectives and requirements defined should contribute to one or more of the research campaigns. Scientific requirements can also be agreed with partners where a mission is conceived jointly with other organisations.

Step 2: Issue Request For Information and identify payload options. Information on possible payloads that could achieve those science requirements is then sought through an RFI. The RFI should specify scientific objectives and requirements and outline the expected scope of the mission. Responses to the RFI constitute a pool of payloads which can be considered as possibilities to be considered in the context of mission studies.

Step 3: Prepare strawman payload for studies. A scientific and technical review of the RFI inputs should be performed to down select payloads to be considered as a strawman payload. The strawman payload exists for the purposes of the mission study phase to inform and challenge mission requirements definition and mission design. Payload study activities should be initiated to inform mission studies on operations, scientific performance, and interfaces, as well as ensuring that payload candidates achieve a minimum level of readiness consistent with that of the mission.

Step 4: Issue Announcement of Opportunity. Upon approval for a mission, or at the beginning of Phase B2, whichever is earlier, the payload shall be selected. Selection shall be made on the basis of an Announcement of Opportunity (AO). An AO should present the mission, strawman payload, interfaces, a concept of operations, and all relevant boundary conditions. Payloads should typically be led by a Principal Investigator (PI), although alternative approaches may be established where appropriate (see Section 13).

Selection of the payloads shall be made based on an assessment of:

- Heritage, Technology Readiness Level and current level of maturity.
- Scientific performance in relation to the specified science requirements.
- Development needs to achieve flight readiness.
- Accommodation and interface requirement compliance.
- Science team background and ability to support the payload and its science exploitation (including confirmed funding for data analysis).
- Science operations concept.
- Budgetary constraints and requirements.
- Risks.

Step 5: Select payloads and initiate developments. Once selected, payloads enter into a development phase preparing for flight and are integrated with the mission for which a unique Science Management Plan shall be developed to define the organisation of science and payloads at project level.

Payload funding approaches

Payloads are presumed to be developed through ESA funding. Alternative funding approaches could be explored on an ad hoc basis where deemed more appropriate (e.g. funding from national agencies, institutional funding, or from other third party sources).

Identification of funding approaches for the payload shall be part of the assessment for selection. For Missions of Opportunity, an ESA allocation for payloads shall be assigned for a given flight opportunity. Commitment from other sources of funding for any additional costs shall be a requirement for selection. For Directed Missions, the full cost of instrument development would notionally be taken on by ESA, although alternative funding approaches could be considered.

12 SAMPLE ANALYSIS

In preparation for future sample return missions from the Moon and other destinations a transition is needed from a collection of centres working independently on ad hoc projects, to a Network of Centres working in a coordinated, structured and integrated way. A Network of Centres must have the appropriate capabilities and expertise for sample analysis, sample curation, sample allocation, and research management. Approaches to establishing these capabilities need to be compatible with the needs of all future missions, such that they can be applied to missions returning samples from the Moon, Mars and other destinations.

A European Sample Analysis Network of Centres shall be established as a virtual cross-European institute for sample analysis. Initially the network will use near-term opportunities provided by international partners or meteorites and analogue materials to perform sample analysis investigations. The investigations will involve multi-centre research on common samples to deliver new science whilst preparing the organisation structures, management and curation standards and approaches, lessons learned, analytical capabilities, and technical requirements to prepare for future missions. Such a network could be extended beyond Europe through bilateral or multilateral agreements. This is currently under discussion with CNSA.

An evolved network would eventually provide sample analysis facilities to support future sample return missions, using nearer term opportunities and Moon mission samples to prepare for Mars.

Samples delivered through European missions would first be available to this network for an initial structured and coordinated sample analysis campaign, which may involve international partner laboratories. After the initial analysis campaign is completed, samples would be curated and made available to the broader scientific community in Europe and beyond through a managed process of allocation based on scientific proposals.

13 SCIENCE ROLES

Different modes for participation in lunar missions need to exist, recognising the diversity and variability of opportunities that might be expected. It is important to recognise that a “one size fits all” approach will probably not apply. This may be particularly true for missions led by international partners where alternative science management approaches may be applied.

The initial envisaged approaches to science participation are described below. Bespoke engagement opportunities may be defined later.

Principal Investigators (PIs) are responsible for the definition, development and delivery of a payload to ESA for flight, for the scientific operation of the payload, for the establishment and management of the science team in support of the payload's science, and for the delivery of scientific data products to ESA for archiving and publication of scientific results. PIs are formally selected at the time of payload selection for flight. An example of PI roles and responsibilities is provided in [RD9].

Investigation Leads (ILs) are responsible for leading a scientific investigation that uses ESA supplied payloads or samples delivered through ESA, and are selected through formal Announcements of Opportunity. ILs are also responsible for the scientific operation of payloads for the establishment and management of the science team to perform the given investigation, and for the delivery of scientific data products and results to ESA for archiving and publication. ILs have no obligations linked to hardware delivery. An example of IL roles and responsibilities is provided in [RD10].

Co-Investigators (Co-Is) are appointed by PIs or ILs as part of a payload's or an investigation's science team and have confirmed funding to support their activities within the science team. Co-Is have obligations associated with their contributions which are defined by the PI or IL.

Payload/Investigation Science Team Members include all acknowledged members of a payload or investigation science team including PIs, ILs, Co-Is and other members of the science team who contribute to the science but may not be funded for their involvement. Science Team Members who are not Co-Is shall not have obligations within a science team upon which hardware delivery, science operations, or data product delivery is dependant.

ESA Study/Project Scientists are appointed by ESA and have responsibility for science management of a project within the ESA programmatic framework. Study scientists are assigned during the study phases of a project. Project scientists are assigned as soon as a mission is approved or at the end of Phase B1 (SRR), whichever occurs first. Project/study scientists are responsible for:

1) The definition of science objectives and requirements and tracking the scientific performance of a project, including both mission and payload against these requirements throughout a project's life cycle.
2) Representing the interests of scientific users within mission and payload studies and development activities, and providing the interface between PIs, ILs and ESA study activities.
3) Ensuring the realisation of the planned scientific outcomes of a mission, and the establishment of scientific infrastructure and capabilities needed to deliver these.
4) Implementing benefit management as the benefit owner for scientific benefits.
5) The interface between PIs and ESA mission teams or between ILs and ESA facility payloads.
6) Management of mission science teams made up of PIs and ILs.

A Project/Study scientist interfaces directly with the project manager but does not report to the project manager.

14 SCIENCE GROUND SEGMENT AND FACILITIES

Ground research facilities will be required to support research activities at the Moon. These facilities may relate to calibration, performance testing, environmental testing, operations preparation and testing, or provide supporting measurements and experiments.

In general, it is assumed that access to bespoke ground facilities and those needed for payload developments will be addressed as a part of payload development activities.

It may be however that within the various areas of investigation there are key ground capabilities that should be made available to the broader community. An objective will be to identify facility needs, identify where facilities exist that meet those needs, and to identify gaps. Where facilities exist, approaches should be developed to assure access for the community who are engaged in ESA missions. Where gaps exist, approaches to filling the gaps need to be identified and addressed.

For all missions, science operations infrastructure is required. ESA shall ensure that the required infrastructure exists to support payload operations for both Missions of Opportunity and Directed Missions. Appropriate infrastructure and capabilities shall be made accessible to science teams during the mission, with appropriate technical support. Support shall be made available to science teams in preparing their science operations approaches.

Part of the approach to this will be the standardisation of infrastructure and interfaces wherever possible, and the securing of lessons learned. The approach shall be to use distributed and decentralised infrastructures where possible, whilst ensuring that centralised facilities are available where needed. Where feasible, commercially provided science operations infrastructure shall be used.

15 DATA POLICY

All data generated will be processed, stored, and made available in line with the documented Human and Robotic Exploration Data Policy [RD11]. All data generated by payloads and derived data products will be made available via ESA’s data archives after a proprietary period (usually 6 months).

Bespoke definitions of data products to be delivered, and obligations for PIs and ILs shall be defined for each payload or investigation.

16 SCIENCE OVERSIGHT

Overall scientific oversight of lunar science activities is provided by the Human Spaceflight and Exploration Science Advisory Committee (HESAC).

A multidisciplinary Lunar Science and Research Team will be established to provide ongoing consultation on the science strategy and its implementation, and to provide an interface with the science community. The team will monitor progress in the various campaigns and advise on priorities and approaches for following steps. The team will include members representing the various disciplines of the science campaigns and nominated members from the following science working groups of the Agency: Physical Sciences Working Group (PSWG), Solar System Exploration Working Group (SSEWG), Life Sciences Working Group (LSWG), Astronomy Working Group (AWG). These members represent the communities of the working groups who may also be consulted as needed. Members may also be nominated from relevant Topical Teams and from other initiatives within the programme.

17 REFERENCE DOCUMENTS

RD1. National Research Council, The Scientific Context for Exploration of the Moon. National Academies Press, Washington DC, 2007. https://www.nap.edu/login.php?record_id=11954&page=https%3A%2F%2Fwww.nap.edu%2Fdownload%2F11954

RD2. Moon the 8th Continent, ESA, Final Report of the Human Spaceflight Vision Study Group, 2003. https://www.lpi.usra.edu/lunar/strategies/Moon_The_8th_Continent.pdf

RD3. Crawford, C., Anand, M., Cockell, C., Falke, H., Green, D., Jaumann, R. Wieczorek, M., 2012. Back to the Moon: The scientific rationale for resuming lunar surface exploration, Planetary and Space Science, 74, 3–14. https://www.sciencedirect.com/science/article/pii/S0032063312001444

RD4. International Space Exploration Coordination Group, Scientific Opportunities Enabled By Human Exploration Beyond Low-Earth Orbit, 2018. https://www.globalspaceexploration.org/wordpress/wp-content/isecg/ISECG%20SWP_FINAL-web_2017-12.pdf

RD5. ESA, Lunar Sample Return Science Objectives and Requirements Definition, 2014.

RD6. ESA, Science and Challenges of Lunar Sample Return: Workshop Outcomes and Recommendations, 2014. https://www.lpi.usra.edu/lunar/strategies/WorkshopOutcomesRecommendations033114.pdf

RD7. Lunar Exploration Objectives and Requirements Definition, LL-ESA-ORD-413, 2010.

RD8. Jawin, E.R., Valencia, S.N., Watkins, R.N., Crowell, J.M., Neal, C.R., Schmidt, G., Lunar Science for Landed Missions Workshop Findings Report, https://lunar-landing.arc.nasa.gov/downloads/LunarLandedScience_ReportSummary_082818.pdf

RD9. ExoMars Science Management Plan, ESA/PB-HME(2014)2

RD10. Announcement of Opportunity: PROSPECT Science Team, ESA-HRE-PROSPECT-AO-0001, 2018. https://www.cosmos.esa.int/web/prospect/ao-prospect-science-team

RD11. Human and Robotic Exploration Data Policy, ESA/PB-HME(2018)35

ANNEX 1: RATIONALE FOR RESUMING LUNAR SURFACE EXPLORATION

This annex presents the results of a review of the scientific content that was presented in 2012, RD3. The review was tasked with identifying scientific topics that should be added or updated, compared with the scientific topics presented in RD3, as a result of omissions in the original science case or recent scientific results. This review was performed by the science team presented in Annex 2 to provide a scientific rationale for resuming lunar surface exploration.

The outcomes of this review are presented here with a structure following the contents of the science strategy document reflecting science of the Moon, on the Moon, from the Moon, and applied science and technology research.

Science of the Moon

Science of the Moon includes research into the origin, and evolution of the Moon, and its present day environment. Topics and major research themes regarding Science of the Moon are summarised in Table 3.

Topic	**Major research themes**
Bombardment	Cataclysm? Inner solar system chronology – all planets?
Structure from core to crust	How did the Moon differentiate? Why was the subsequent thermal and volcanic evolution asymmetric between the near side and far side hemispheres?
Rock diversity and distribution	Crust homogeneity and evolution (LMO, KREEP etc.)?
Polar volatiles (ice)	Origins? Distribution? Abundances? Processes? Resources?
Volcanism	How recent? Role of volatiles? Thermal evolution? Interior diversity? Resources?
Impact processes	The Moon is a natural laboratory for impact events at all scales. The Moon and Earth were subjected to the same impact environment.
Regolith	Formation and weathering processes? History of the Sun and Solar System? Resources?
Atmosphere and dust	Exosphere formation and evolution? Dust levitation and transport?
Earth-Moon formation	When? How? Subsequent evolution and processes on Moon and Earth?

Table 3 – Science of the Moon: topics and major research themes.

Science topics that should supplement the baseline science case for science on the Moon outlined in RD3 are described in this section, based on new research results or a more detailed consideration. The priorities for activities to be performed that can address these science topics are described below.

Increase the diversity of lunar rocks in the sample collection. New lunar samples should be from diverse lithologies including new samples of mare basalts, especially those that appear 'young' based on crater counts, samples of different ages including the oldest impact basins, and plutonic samples (e.g. Mg suite). Dating these samples and analysing their composition and mineralogy will:

- better constrain the cratering rate throughout Solar System history
- test the global distribution of the Lunar Magma Ocean
- test the global distribution of volatile loss and isotopic fractionation
- inform models of lunar mantle evolution
- assist in the interpretation of palaeoregoliths found trapped between basalts

[see also RD5, RD6].

Improving the calibration of the cratering rate would be of great value for the whole of planetary science, including the science of the early Earth. Lunar chronology is poorly constrained at ages older than 3.9 Ga, thus sample return and in situ radiometric age dating of well-understood samples (e.g. impact melts) could fill this knowledge gap. Similarly, there are no data points in the lunar chronology between 3.2 and 1 Ga. Chang'E5 will sample young basalts NE of Mons Rümker, which can provide part of the required information.

The ages of Copernicus, Tycho, North Ray, and Cone craters are less certain than one would prefer and need to be augmented/replaced with samples from a better understood geologic context. Despite these caveats, the Crater Size and Frequency Distribution method works well and can accurately reproduce sample ages. This method will be further improved by adding additional data points to the chronology curve, preferentially outside the 3.2-3.9 Ga time period. The lunar chronology is also extrapolated to date any surface in our Solar System. Thus, sampling of old (>3.9 Ga) well-understood lunar terrain and/or mare basalts that are 1-3 Ga is of highest priority. A focus should be placed on establishing a strong geological understanding of landing sites and accomplishing a few scientific questions, rather than accessing highly optimal and complex landing areas for which interpretation of samples is very challenging.

Deploy geophysical instruments and build up a global geophysics network. Deployment of such instrumentation and an eventual network would constrain models of the lunar interior and address questions on present day seismic activity. Both seismic and heat-flow measurements are required with global coverage. Laser retroreflectors are required at new locations at the surface.

Return samples of previously unsampled regolith and pyroclastic deposits. Analysing samples of new pyroclastic deposits can constrain the thermal evolution, and volatile inventory of the lunar interior. New regolith samples would also provide insight into the processes of regolith formation and maturation, and the diversity of the source rocks from which it formed. There is also synergy between science and exploration as scientific understanding of these samples will inform of their potential as resources.

In situ characterisation of water ice and other volatiles at polar locations. In situ measurements would constrain the sources of polar volatiles and their evolution. Both ice within Permanently Shadowed Regions and the hydrated regoliths, as apparently identified in M3 data at high but not permanently shadowed latitudes, should be included. In both cases the physical and chemical state of the water, its concentration, and its vertical and lateral distribution within the uppermost few metres need to be determined, as well as the presence of other volatiles and organics. Special attention should be paid to the possible synthesis of organic molecules in polar ices by cosmic ray irradiation as this is potentially a natural Urey-Millar experiment of astrobiological relevance.

Addressing the above would require in situ measurements at diverse locations across the polar region, and sampling with both lateral and vertical variation.

Activity	Approach
Determine ages of basins and young lavas	Sample return from locations with diverse ages based on crater counting
Characterise the internal structure and thermal state of the lunar interior	Seismometers, heat flow probes, and laser retroreflectors at one or multiple locations (network)
Characterisation of polar volatiles	Surface and subsurface in situ measurements, diverse locations, eventual sample return
Diverse sampling of mare basalts	Near side diverse locations, sample return and in situ measurements, mineralogy, chronology, and composition
Identification and sampling of palaeoregolith deposits trapped between lava flows	Deep drilling and sample return

Table 4 – Science of the Moon: research activities and approaches.

The bombardment history of the inner solar system

The content of RD3 is considered sufficient.

Structure and composition from core to crust

In addition to the content of RD3 the below aspects are considered important.

During the last decades, increasing evidence has emerged indicating lateral and vertical compositional heterogeneity within the lunar interior, which is in contrast with the standard magma ocean scenario view. Additional studies also question the traditional crustal organisation as presumably inherited from the lunar magma ocean stage. It is suggested that the far side highland crust is more magnesian than the near side crust, based on remote sensing data and meteorite analysis, implying that composition of the magma ocean may have been more primitive at the time of crustal growth than previously estimated. This potentiality is at odds with the previously accepted theory that primitive crust forming ferroan anorthosites (FANS) were inherited from the magma ocean stage while the Mg-rich suite from the Apollo collection, which are relatively younger, formed from subsequent intrusive magmatism.

This challenge to our current understanding of lunar evolution demonstrates a more general trend in which the existing paradigm of understanding is being challenged by new evidence, revealing that current models for lunar evolution are far more uncertain than previously thought.

For example the thermal effect of the mega-regolith is an area which requires additional effort. Insulating effects of the porous mega-regolith may have had substantial implications for the thermal history of the Moon, resulting in a much slower cooling of the interior than would be the case without a mega regolth.

Interior volatile investigation remains a top priority for understanding the composition and evolution of the Moon, particularly with regard to addressing the question of how wet is/was the Moon?

Rock diversity and distribution

In addition to the content of RD3 the below aspects are considered important.

While it is true that we have only basic knowledge of the diversity of lunar rocks, there are also important questions relating to the spatial distribution of rock types. A major example of importance is the distribution of KREEP at the base of the crust where its distribution may be in a continuous layer or in discrete pockets. It also has an apparent concentration in the Procellarum KREEP Terrain (PKT) on the near side and apparent absence from the far side. It is also important to determine the seeming connection between KREEP and the occurrence of young basalts.

Water ice and other volatiles at the lunar poles

While the existing science case in RD3 highlights the importance of polar volatiles, the more recent research has continued to increase the evidence base for their existence. This has naturally raised additional science questions regarding their abundance and distribution. Particularly important results have been obtained from analysis of measurements made by instruments on the Lunar Reconnaissance Orbiter (LAMP, Mini-RF, LOLA) and Chandrayaan (M3). Indications now show that water ice is present at the surface in some permanently shadowed craters, with concentrations as high as 30%. The distribution of these volatiles across the polar regions may result from the evolution of the spin axis of the Moon through true polar wonder, the slow shifting of the position of the rotational pole of the Moon over time. This has important implications for the ages and origins of polar volatiles.

Volcanism

The science case for investigations into lunar volcanism is more extensive than previously indicated with many open areas of investigation that are not addressed in RD3. These include the incomplete filling of SPA, the potentially extremely young ages of irregular mare patches, variation in igneous compositions, eruption style, the origin of the magnesium suite, and potential ISRU use. Many of these overlap significantly with other identified research areas. One topic of particular note is the newly observed volcanic features on the Moon that are potentially much younger than anything previously observed. These are the Irregular Mare Patches (IMP) and Ring-Moat Dome Structures (RMDS). The apparent ages of these features would require that lunar volcanism continued until more recently than previously thought possible. If this is the case, then it poses major questions for models of lunar thermal evolution. What is certainly clear is that lunar volcanism is much more diverse than had previously been thought.

Another new element has been the recognition that intact lava tubes might be more common than previously thought, as indicated by interpretations of GRAIL gravity data.

Impact processes

A long list of areas of investigation exist in relation to impact processes which should be addressed in addition to those identified in RD3. Examples include:

- the effects of target properties on the formation of small, strength-dominated craters.
- the recent impact rate and its comparison model predictions.
- the variability with space and time of impact rate during the last 3 Ga.
- the production of impact melt in any given crater and the definition of impact melt.
- the morphological distinction between impact melt and volcanic filling of craters.

Regolith processes

The content of RD3 is considered sufficient in this area.

Atmospheric and dust environment

Dust transportation and levitation is an important aspect to understand, as noted in RD3. It is also relevant for asteroids and so whatever we can learn about this topic on the Moon will benefit our understanding of these processes on asteroid surfaces.

Earth-Moon formation and history

This section is an addition to the topics identified in RD3. Although referred to in RD3, its importance is such that it should be singled out as a stand-alone topic.

Of particular importance is the age of the Moon and the Earth. It is currently not universally agreed whether the Moon formed early (i.e. 50-100 Myrs) after Solar System formation or later (i.e. more than 200 Myrs).

The scientific questions regarding the age of the Moon and of the purported giant impact that led to its formation also have a significant impact for models of the Lunar Magma Ocean (LMO). If the Moon formed early but analysis of mare basalts and anorthosites indicate a late age for LMO crystallisation, then it would have major implications with regards to the cooling regime of the magma ocean. Cooling is currently understood to have lasted less than 10 Myrs. It might also indicate that the LMO does not represent a primordial melting of the Moon.

Another major discovery since 2012 has been the existence of isotopic variations between the Moon and the Earth in moderately volatile elements (e.g. Zn). These discoveries generally imply a loss of these elements from the material that formed the Moon, either during giant impact event(s), or through later loss processes. This has important implications for models of Moon formation and early evolution, particularly with regard to the processes of heavy element loss and the overall temperature of the system.

Evidence for indigenous water from analysis of the ancient lunar rocks collected by the Apollo missions has been discovered in the past decade. Indigenous water was also detected remotely in the central peak of Bullialdus crater, where rocks from the subsurface have been excavated, and in pyroclastic deposits. Petrological experiments show that a small amount of water in the initial magma ocean would be more consistent with the GRAIL crustal thickness.

A key question that now exists is: how wet is the Moon?

One unexpected recent result has been the indication that the Moon may have had a ~10 mbar transient atmosphere for tens of millions of years around 3.5 Ga due to volcanic out-gassing. This is greater than the present atmospheric pressure on Mars, and above the triple-point pressure of water. The Moon may even have been habitable briefly. One way to test this hypothesis is by sampling palaeoregoliths from this time period.

Lunar tectonics

An additional topic not addressed in RD3 is lunar tectonics. New LROC high-resolution images have enabled the study of more than 3000 small-scale compressional features that were most likely formed by thermal contraction and tidal forces. Some of those show very recent ages, which are consistent with their very pristine and sharp morphology. If correct, this would imply that the Moon was still geologically active up until only a few 10s of million years ago. This needs to be further tested and studied through the return of samples to measure exposure ages.

An additional aspect for research is the difference between Mercury where very large scarps are observed, and the Moon where they are not. Investigations should determine how the stress field is different and why and what this implies for the thermal history of both bodies.

Science on the Moon

Science on the Moon refers to the use of the lunar surface as a research destination to perform scientific research that is broader in scope than science of the Moon. The Moon in this case is not the subject of the research but rather a facility for research. Topics and major research themes regarding science on the Moon are summarised in Table 5.

Topic	**Major research themes**
Habitability of the Earth through time	Bombardment, volatiles and organics delivery,
Life in the Universe	Investigation of biological systems in the interplanetary environment
Human exploration	Microbe and plant survival
Physiology and medicine	Physiological effects of partial g, implication for vestibular disorders, aging, disuse pathology, lifestyle conditions (e.g. cardiovascular disease)
Fundamental Physics	Testing General Relativity
Space Physics	Heliosphere/magnetosphere/particle/ExB/surface interactions
History of Sun and Solar System	Age of the Sun? Solar wind composition and evolution, extrasolar material.
Impact rate	Present day impact rate and meteoroid sources

Table 5 – Science on the Moon: topics and major research themes.

The priorities for research activities to be performed in regard to science on the Moon are presented below.

Return samples which reveal the impact bombardment of the early Earth. As described in the section on science of the Moon, the return of samples representing the ages of formation of the major impact basins would constrain the bombardment history of the Earth-Moon system and help to identify if there is coincidence of bombardment and life's emergence on Earth. This may relate to habitability and the formation and delivery of the key ingredients for life.

In-situ analysis and return of lunar polar volatiles. These materials may represent a record of volatile delivery and impacts throughout the history of the Solar System. This would provide insight into the origins of life enabling chemistry on Earth and the relationships between these volatiles and those found on other Solar System bodies. This is also referred to in science of the Moon.

Visit and sample crash sites of Apollo LM ascent stages. This would allow an assessment of survivability of bacteria, spores, and/or organic molecules after 50 years of exposure to the lunar environment. Analysis would inform fundamental biology, planetary protection, and lithopanspermia. Assessing the survivability of organisms (e.g. bacteria, plants) in the lunar environment would be a precursor to future human activities, including agriculture.

Establish what is required to enable life (microbes, plants) to survive in the lunar environment. This involves analysis of the effects of the present-day lunar environment on biological systems and understanding the implications for robotic and human exploration. It also includes assessing what additives are required to lunar regolith to enable it to support biological growth, and the requirements for radiation and thermal protection using countermeasures and lunar materials.

Return and analyse lunar palaeoregolith deposits trapped between lava flows. Palaeoregoliths have potentially preserved records of solar activity, GCR flux (and thus galactic environment), Earth's atmosphere, terrestrial meteorites, and perhaps an early lunar atmosphere. Accessing these records would require targeting palaeoregoliths, for example in various parts of Oceanus Procellarum, which will likely require deep drilling to access subsurface layers. This would most likely be an activity to be undertaken during human missions.

Topic	**Approach**
Assess survivability of organisms and microrganisms	Identify, visit, and sample crash sites of Apollo LM ascent stages, biological growth and exposure experiments
Test ISRU feasibility	Extract water from PSRs, extract oxygen from regolith, sinter regolith, metal production
Test General Relativity	Deploy laser retroreflectors at diverse locations
Physiology in the lunar environment	Representative biological models and human subjects at the lunar surface

Table 6 – Science on the Moon: topics and research approaches.

In the following sections, updates to the content presented in RD3 are presented either based on new science or on requirements to elaborate on and build on the science case previously presented.

Habitability of the Earth through time

The content of RD3 are considered sufficient in this area.

Life in the Universe

The content of RD3 are considered sufficient in this area.

Survivability in space

The content of RD3 are considered sufficient in this area.

Biology and physiology

Measurement in situ or on return to Earth of the biological impact of the lunar environment (radiation and gravitational) is vital to understand the fundamental effects of lunar hypogravity, the unique radiation environment (and their interaction) upon cellular function.

As no current ground-based analogues adequately reflect either the complete radiation spectrum or chronic hypogravity, such studies can only be performed on the lunar surface.

From cellular (or candidate organism) studies, knowledge will then be used to inform experiments and modelling of the impact of the lunar environment at tissue, organ, and organism (human, and potential viral and bacterial companions) levels.

These were not considerations during the Apollo programme where lunar sojourns (max 3 days) and transit times of approximately 4.5 days (i.e. exposure to microgravity) were short. As a result, significant physiological de-conditioning, and secondary to cellular changes associated with prolonged periods in microgravity were not observed. Thus, whether 0.16 g is sufficient to prevent the physiological de-conditioning in numerous physiological systems, or whether it induced de-conditioning plateaus over time remains undetermined. In fact, the threshold of cells and systems to gravity is unknown and thus hypogravity data is vital (to complement data in 1 and 0g) to understand such sensitivity both when in a 'mature' state but also during development. For instance, whether 0.16g is sufficient to promote the normal development of the systems such as the vestibular system is unknown. Indeed a 'critical' window may exist for the vestibular system, similar to that observed for the visual system. As the vestibular system impacts on the regulation of a range of other systems this may have widespread effects.

Furthermore, whilst the dynamic radiation environment of the lunar surface (beyond the protection of the Van Allen belt) has been relatively well characterised, the relationship between radiation dose and downstream biological effects is multi-factorial, and largely unknown. The radiation dose associated with the Apollo missions appeared to be insufficient to generate immediate effects or a statistically significant increase in longer term effects, although identification of the latter is challenging given the low sample number. In addition, the Apollo missions, perhaps fortuitously did not coincide with solar flares.

Whilst prolonged periods on the lunar surface will be associated with significantly elevated radiation exposure likely to induce DNA and downstream cellular damage, the actual severity and risks associated with it are almost entirely unknown. Therefore data that can be used to generate valid models of radiation damage probability are vital to inform human mission risk assessment and determine the requirements for mitigation strategies within mission architectures.

Fundamental physics

It is understood that general relativity is not the universal and ultimate theory of gravity and continued testing of the theory is needed in order to eventually improve our understanding. The Moon-Earth-Sun system can be a precision laboratory of geo-metrodynamics to both identify where general relativity will fail, and to provide experimental hints which may lead to next-generation theories of fundamental gravity. For example, is G constant and is Inverse Square Law (isl) non-newtonian in the weak-field slow-motion regime?

The 2-body Moon-Earth and 3-body Moon-Earth-Sun systems are proven, effective laboratories for precision tests of general relativity in the weak-field slow-motion regime. They are so in a way that is quantitatively and qualitatively complementary to observations of Gravitational Waves by ground interferometers (LIGO, Virgo) and by future research programs. With regard to the latter, e-LISA in space and Einstein Telescope on ground will be operational in the beginning to mid-2030s.

Space physics

While not described explicitly in RD3 the role of the Moon as a laboratory to study space physics is also considered important. These investigations include the interactions between the solar wind and the lunar surface, the Moon's mini magnetic fields, and the role of the Earth's magnetosphere in the overall system.

Investigations could include space plasma instrumentation at the lunar surface and in orbit, as well as x-ray and UV imaging of the Earth's magnetosphere from the Moon.

History of Sun and Solar System

In addition to the points made in RD3, it is worth noting that elements and gases implanted in lunar soils have been and can be used as a record of solar wind composition. Measurements can include determination of the oxygen isotopic composition of the Sun that was measured in implanted solar wind at the surface of metal grains of the regolith.

Impact rate

The content of RD3 is considered sufficient with regard to this topic.

Science from the Moon

Science from the Moon refers to the use of the Moon as a platform for astronomical observations. The priority area in this case has long been established.

Topic	Major research themes
Radio Astronomy	"dark ages" (HI at redshift z=80, i.e. several tens of millions of years after big bang) radio experiment (2-60 MHz)
Optical and IR Astronomy	Determine feasibility in the lunar environment
Galactic Cosmic Ray Sources	Determine the feasibility of angle resolved GCR astronomy

Table 7 – Science from the Moon: topics and major research themes.

Deploy long wavelength radio receivers on the lunar far side. The objective would be first to test and demonstrate the suitability of the environment for cosmic "dark ages" astronomy and then to follow this by the first measurements of the red shifted HI line. Eventually deploying the first interferometer through a network of antennae would be the objective.

Radio astronomy. While addressed in RD3, it is important to emphasise the importance of a “dark ages” (HI at redshift z=80, i.e. several tens of Million years after big bang) radio experiment (2-60 MHz). A first experiment can be performed using a tripole antenna in a quiet location, removed from an operational lander or any source of interference at a far side location.

Other astronomical observations. The Moon can also be a platform for observations at other wavelengths, in particular optical and infra-red telescopes and interferometers. In this case the priority would be to investigate the suitability of the environment for such activity.

In addition, it could be that cosmic ray detectors at the bottom of lunar bore holes might enable high-angular resolution cosmic ray astronomy. This assertion could be tested.

Topic	Approach
Low frequency radio antennas	Deploy radio antennas on the far side. Initially simple tripoles. Later interferometer.
Assess suitability for optical/IR astronomy	Characterise lunar surface dust environment and effects
Identify GCR sources	Assess feasibility of GCR measurements from deep boreholes to achieve directionality

Table 8 – Science from the Moon: topics and research approaches.

ANNEX 2: LUNAR SCIENCE TEAM

An ad hoc science team was assembled in 2018 to prepare the scientific content of the Strategy for Lunar Science at the Moon (Table 9). The team was appointed in October 2018 following endorsement and nomination by the Human Spaceflight and Exploration Science Advisory Committee (HESAC).

Team Members	General Topic	Affiliation
Ian Crawford	Lunar science and exploration	Birkbeck University of London
David Green	Physiology	Kings College London
Charles Cockell	Astrobiology	University of Edinburgh
Mark Wieczorek	Geophysics/interior	Observatoire de la Côte d'Azur
Elke Rabbow	Astrobiology	DLR
Harry Hiesinger	Geology	University of Muenster
Maria Cristina de Sanctis	Planetary geology	INAF
Simone Dell'Agnello	Physics	INFN
Mahesh Anand	Samples	Open University
Fred Moynier	Samples	IPGP
Ralf Jaumann	Planetary science	DLR
Jessica Flahaut	Geology	CRPG/CNRS
Heino Falke	Astronomy and astrophysics	Radboud University Nijmegen
Nicolas André	Plasma and exosphere environments	IRAP
Urs Mall	Planetary science	Max-Planck-Institut für Sonnensystemforschung
Elena Pettinelli	Surface and subsurface geologic structure	Università degli Studi di Roma Tre
Javier Martin-Torres	Atmospheric science, ISRU, habitability	Lulea University of Technology
Marjan Moreels	Radiation protection	SCK-CEN, Belgian Nuclear Research Centre

Table 9 – Lunar Science Team members

ANNEX 3: COMPARISON OF ISECG, LUNAR, AND ESA SCIENCE THEMES

		ISECG Science Themes						
		Understanding our place in the universe						**Living and working in space**
	ESA Grand Science Themes	Terrestrial and Cosmic Climate	Understanding Gravity	Life in the Universe	Cosmic Radiation and Magnetism	Grand Astronautical Challenges		
						New observing locations	Space debris and near-Earth objects	Long-distance space travel
Lunar Science Themes	**Of the Moon**							
	Bombardment	🟩		🟩				
	Structure from core to crust		🟩	🟩	🟩			
	Rock diversity and distribution			🟩	🟩			
	Polar volatiles (ice)	🟩		🟩				🟩
	Volcanism			🟩	🟩			🟩
	Impact processes			🟩		🟩	🟩	🟩
	Regolith	🟩		🟩	🟩	🟩	🟩	🟩
	Atmosphere and dust	🟩			🟩	🟩		🟩
	Earth-Moon formation			🟩				
	On the Moon							
	Habitability of the Earth through time	🟩		🟩				
	Life in the Universe	🟩		🟩				
	Survivability in space			🟩				🟩
	Physiology and medicine							🟩
	Fundamental Physics		🟩			🟩		
	Space Physics	🟩			🟩			🟩
	History of Sun and Solar System	🟩		🟩	🟩			
	Impact rate						🟩	🟩
	From the Moon							
	Radio Astronomy		🟩			🟩		
	Optical & IR Astronomy		🟩	🟩		🟩		

Table 10 – Comparison of ESA grand science themes with ISECG science themes and lunar science themes.

ANNEX 4: APPLICATION OF CAMPAIGNS FOR SCIENCE AT THE MOON

Topic	**Major Research Topics**	**Campaign 1: Samples**	**Campaign 2: polar volatiles**	**Campaign 3: Geophysics**	**Campaign 4: plasma, exosphere, dust**	**Campaign 5: In situ geoscience**	**Campaign 6: Physiology & biology**	**Investigation 7: Physics and astronomy**
Bombardment	Cataclysm? Inner solar system chronology – all planets?	🟩				🟨		
Structure from core to crust	How did the Moon differentiate? Why was the subsequent thermal and volcanic evolution asymmetric between the nearside and farside hemispheres?	🟩		🟩		🟩		
Rock diversity and distribution	Crust homogeneity & evolution (LMO, KREEP etc.)?	🟩		🟩		🟩		
Polar volatiles (ice)	Origins? Distribution? Abundance? Processes? Resources?	🟩	🟩		🟨			
Volcanism	How recent? Role of volatiles? Thermal evolution? Interior diversity? Resources?	🟩	🟨					
Impact processes	The Moon is a natural laboratory for impact events at all scales. The Moon and Earth were subjected to the same impact environment.	🟩	🟨	🟨	🟨	🟨		
Regolith	Formation and weathering processes? History of the Sun and Solar System? Resources?	🟩	🟨	🟨	🟨	🟩	🟩	🟨
Atmosphere and dust	Exosphere formation and evolution? Dust levitation and transport?				🟩		🟨	🟨
Earth-Moon formation	When? How? Subsequent evolution and processes on Moon & Earth?	🟩				🟨		

Table 11 - Contributions of the campaign investigations to science of the Moon.

Topic	Major Research Topics	Campaign 1: Samples	Campaign 2: polar volatiles	Campaign 3: Geophysics	Campaign 4: plasma, exosphere, dust	Campaign 5: In situ geoscience	Campaign 6: Physiology & biology	Investigation 7: Physics and astronomy
Habitability of the Earth through time	Bombardment, volatiles and organics delivery,	🟩	🟩	🟨		🟨	🟨	
Life in the Universe	Investigation of biological systems in the interplanetary environment	🟨	🟨		🟨		🟩	
Human exploration	Microbe and plant survival	🟨	🟨			🟨	🟩	
Physiology and medicine	Physiological effects of partial g, implication for vestibular disorders, aging, disuse pathology, lifestyle conditions (e.g. cardiovascular disease)	🟨			🟨		🟩	
Fundamental Physics	Testing General Relativity			🟨				🟩
Space Physics	Heliosphere/magnetosphere/particle/ExB/surface interactions				🟩			
History of Sun and Solar System	Age of the Sun? Solar wind composition and evolution, extrasolar material.	🟩						
Impact rate	Present day impact rate and meteoroid sources	🟩		🟩	🟨			

Table 12 - Contributions of the campaign investigations to science on the Moon.

Topic	Major Research Topics	Campaign 1: Samples	Campaign 2: polar volatiles	Campaign 3: Geophysics	Campaign 4: plasma, exosphere, dust	Campaign 5: In situ geoscience	Campaign 6: Physiology & biology	Investigation 7: Physics and astronomy
Radio Astronomy	"dark ages" (HI at redshift z=80, i.e. several tens of Million years after big bang) radio experiment (2-60 MHz)							🟩
Optical & IR Astronomy	Feasibility in the lunar environment?			🟨	🟨			🟩

Table 13 - Contributions of the campaign investigations to science from the Moon.

ANNEX 5: RESEARCH CAMPAIGNS

Scientific activities are distributed across seven scientific campaigns. Each of these campaigns includes a set of scientific activities that contribute to one or more of the lunar science topics introduced in Section 4. These campaigns see a sustained build-up of activity in a given scientific area over time. The campaigns will begin with single opportunistic payloads on Missions of Opportunity to address important scientific challenges that require limited mission capability and are compatible with the constraints of early opportunities. The early phases of these campaigns should deliver scientific results, whilst building the scientific community and capabilities needed as the scientific capacity grows on robotic precursor missions and eventually human missions.

These campaigns are:

- Campaign 1: Analysis of new lunar samples
- Campaign 2: Characterisation of cold trapped polar volatiles
- Campaign 3: Geophysical measurements of the lunar interior
- Campaign 4: Plasma, exosphere and dust environment and effects
- Campaign 5: Near surface geology, geophysics, mineralogy and geochemistry
- Campaign 6: Biological and physiological effects of the lunar environment
- Campaign 7: Physics and astronomy from the Moon

The following sections introduce these campaigns and present a notional approach to implementing them over the three envisaged phases of scientific utilisation of the Moon. The rate of advancement of the campaigns can be increased or slowed depending on the availability of opportunities.

Campaign 1: Analysis of new lunar samples

New samples from unexplored and distinct locations across the lunar surface are required to address fundamental scientific questions about the history of the Solar System, the early Earth, and processes of planetary formation and evolution that cannot be answered by any other means.
The analysis of samples returned by the Apollo missions of the USA and the Luna missions of the Soviet Union have provided an unprecedented insight into the origins and evolution of the Earth-Moon system and the impact chronology of the inner Solar System. These insights began when the samples arrived on Earth and continue to the present day. As technology for analysis improves, new techniques are developed and new scientific questions are raised that as new insights continue to be gleaned from these samples. Recent orbital missions have added to this by showing the global context of the samples we have in our collections. It should be noted that these samples have all been obtained from the near side in an area close to the equator and in regions affected by mare volcanism. We now understand that these regions are not representative of the Moon as a whole. The Moon is more diverse, more complex and more important scientifically than we had previously understood, and new lunar samples are key to the realisation of this scientific potential.

Extensive capability and expertise exist in Europe in the area of sample analysis, with world leading laboratories and experts distributed across the continent. European heritage in sample analysis dates back hundreds of years to the first examinations of meteorites and has built continuously on this heritage. The United Kingdom’s meteorite sample collection for example was initiated in 1802. European laboratories were greatly involved in the analysis of lunar samples during the era of Apollo and Luna and continue to make considerable contributions as part of the present resurgence of lunar sample analyses. Between 2014 and 2016, 38% of the 178 new requests for Apollo samples for research came from Europe with 32 different Principle Investigators from 24 different institutions across 6 different European countries.

The scope of science that can be performed with lunar samples is vast, addressing key questions which transcend topics across different areas.

It is important to note that any new lunar samples from any unexplored location will provide new and important scientific insights. In the event that prioritisation is possible than the priorities would be to return and analyse samples:

1. From areas with diverse ages as determined from crater counting, including the oldest impact basins and youngest volcanic units.
2. From diverse locations which include different products of mare volcanism and represent varied stages of planetary differentiation.
3. Containing cold trapped volatiles from polar locations.
4. Palaeoregoliths trapped between lava flows.

In all cases, it is important that sample selection is prepared with additional information recorded in situ to determine the geological context for the samples.

The approach to returning and analysing new samples will require a coordinated and distributed analysis across multiple laboratories with different capabilities and expertise. It will also require a comprehensive approach to sample receiving and curation. These activities should be performed in a way that also prepares capabilities and approaches to be used for samples returned from other destinations, in particular Mars.

Implementation approach

Phase 1

During Phase 1, ESA will not implement any dedicated sample return missions but will work with international partners, where possible, to enable opportunities for European investigators to access lunar samples that are not currently accessible. In doing so, the management, coordination and analytical capabilities needed for future missions from the Moon and Mars shall be identified and approaches to coordinated sample analysis campaigns for new samples will be tested.

Phase 2

During Phase 2, ESA will actively engage in sample return activities that address the identified scientific priorities as part of robotic precursor missions. Lessons learned during Phase 1 in the implementation of sample analysis campaigns, sample management and curation will be implemented in coordination with international partners. All activities will be carried out with the view to optimising synergies with the needs of Mars sample return activities and preparations.

Campaign 2: Characterisation of cold trapped polar volatiles

An increasingly compelling body of evidence exists for the presence of cold trapped water ice and other volatile chemistry at the poles of the Moon. In these locations, areas exist which are always shaded from the Sun and are therefore some of the coldest places in the Solar System. Definitive measurement of the cold trapped ice has been made in some of these permanently dark craters and evidence exists to suggest ice may also exist beneath the surface in near-by areas where heating by the Sun is limited.

These volatile chemicals may have been delivered to the surface by asteroid and cometary impacts, in which case they would provide a time averaged record of the delivery into the Earth-Moon system of the chemicals needed for life. They may have originated from the lunar interior, erupted during volcanic events, in which case they record the volatile content of the interior of the Moon, which is essential for understanding the formation and evolution of the Earth-Moon system. If the volatiles have been produced by interactions between the solar wind and lunar materials, then they contain information on the history of the solar wind and on these complex interactions. They may be a resource for future exploration providing water, oxygen and propellant for future missions. They may provide a natural laboratory for the formation of complex life enabling chemical building blocks through exposure of carbon and other elements in the ices to cosmic radiation and impacts.

At present while their presence is confirmed and their scientific potential is clear, little is known about the abundance, composition, origins or distribution of these volatiles. Measurements of the surface and subsurface are required at different polar locations, to establish the distribution of volatiles species on various spatial scales and in different environments.

The priority for activities to characterise polar volatiles are:

1. Deploy and operate instrumentation in diverse locations at the surface in polar regions to measure the chemical composition and distribution of volatiles.
2. Return and analyse samples of cold trapped volatiles from the lunar poles.

Implementation approach

Phase 1

In Phase 1, opportunities will be taken, where presented, to deliver instrumentation to the lunar polar regions that measure the abundance, distribution and composition of lunar polar volatiles. The first payload in development is the PROSPECT (Package for Resource Observation and in Situ Prospecting for Exploration Commercial exploitation and Transportation) package for the Luna-27 mission. Landers, penetrators and impactors may all offer opportunities for in situ measurements of importance. Supporting measurements made from orbit may also provide useful data.

Instruments of interest for compositional measurements during surface missions include evolved gas analysers, mass spectrometers, neutron spectrometers, and infrared spectrometers. Other instruments providing additional geological context measurements include gamma ray spectrometers and ground penetrating radars.

Cameras for geological context, situational awareness, and public engagement should always be considered in any surface mission.

Phase 2

In Phase 2, instrumentation should be delivered to the polar regions as part of an international effort to explore the lunar polar regions on dedicated missions. ESA instrumentation could be supplied to these international missions if they are realised and participation in lunar polar sample return should be considered as an option if an international partnership opportunity exists.

Missions are required to diverse locations, in permanently shaded regions and in partially shaded regions with different temperatures and with different inferred volatile content, as inferred by remote sensing data sets. Opportunities to advance these activities during Phase 1 should be undertaken as a high priority. Achieving these objectives is dependent on the availability of missions to these locations from commercial actors or international partners.

Phase 3

In Phase 3, human exploration capabilities should be deployed to access lunar polar volatiles, to measure them and to return samples. If shown to be possible then utilisation of these volatiles could be considered as part of human missions.

Campaign 3: Geophysical measurements of the lunar interior

The structure of the lunar interior provides a reference point for our understanding of how rocky planets form, cool, crystallise and separate into compositionally distinct layers. This is a fundamental process of planetary formation and evolution which defines much about the properties and environments of the planets as we see them today. Because of the Moon's small size much of its interior heat was lost early on in its history, around three billion years ago. As a result, many of the processes that could change the structure of the interior stopped and the solidified interior that remained preserved the majority of the primary differentiation; something that has been lost from the larger planetary bodies of the Solar System.

Present knowledge of the structure of the lunar interior has been established through analysis of data from geophysical instruments which were operated at the lunar surface during Apollo. The distribution of these stations fundamentally limits the current view of the lunar interior and many open questions remain on the structure, thermal evolution and the degree of inhomogeneity. In addition, the improved performance of modern instrumentation will allow for significant additional insight compared with the instruments developed in the 1960s. Resolving these questions, which are of fundamental importance for our understanding of the Moon and all the terrestrial planets, requires the deployment of new geophysical stations across the lunar surface and their coincident and long duration operations.

Geophysical stations should include seismometers to map the interior's structure, heat flow probes to measure the outflow of heat from the lunar interior and laser retroreflectors to measure the state of the lunar interior and test fundamental laws of physics. Extensive heritage in such instrumentation exists in Europe with instruments prepared and flown on the NASA InSight mission and studied extensively in the past for lunar applications.

The priority for activities related to geophysical measurements of the lunar interior are:

- Deploy laser retroreflectors to new locations at the lunar surface.
- Deploy and operate at least one complete geophysics package including a seismometer, heat flow probe and laser retroreflector at a location which is geographically set apart from previous sites.
- Contribute to a global network of geophysical instrumentation.

The approach to performing these activities should build extensively on and preserve European existing expertise and capabilities in planetary geophysics and instrumentation, developed in the context of Mars missions, whilst preparing for future Mars geophysics missions.

The establishment of a global geophysical network at the Moon should be pursued as an international undertaking, with contributions from different countries and with commonly agreed approaches to instrument performance, data standardisation and data access.

Implementation approach

Phase 1

In Phase 1, opportunities should be taken to deploy laser retroreflectors to the lunar surface on missions of opportunity to near side locations as a cost effective, low risk and low complexity scientific capability that could be compatible with the simplest of landers available. Where cost and schedule allow, opportunities should be taken to deploy a long lived geophysical station consisting of a seismometer and heat flow probe. A key capability required to achieve this is night survivability and ideally operations.

Phase 2

In Phase 2, a goal should be to achieve a long lived global network of geophysical stations with a broad geographical distribution. This could be achieved through international coordination, defining standards for instrumentation, measurements, performance, data access and locations for deployment. This could build any deployments achieved during Phase 1, adding to them with new stations and instrumentation.

Phase 3

In Phase 3, a continuation of the geophysical station network should be enabled to assure continuous measurements. In addition active measurements and localised networks can be envisaged to probe the shallow subsurface and local geology.

Campaign 4: Plasma, exosphere and dust environment and effects

The lunar environment is characterised by plasmas from the Solar Wind and Earth's magnetosphere; solar, terrestrial and local lunar magnetic fields; electrically charged lunar dust particles and neutral molecules in the tenuous lunar exosphere. These components of the lunar environment coexist and interact providing a reference environment in which we can investigate the processes that take place on any airless bodies.

These environmental conditions also affect systems that are deployed at the surface, charging surfaces and affecting the interactions of dust particles, which have been shown historically to be a limiting factor for surface operations at the Moon.

Characterisation of the environment and its effects requires measurements of neutral particles in the exosphere, ions in the local plasma, magnetic fields, dust particle charges levitation and mobilisation and induced potentials on spacecraft surfaces.

Priorities for activities related to the plasma, exosphere and dust environment and effects are:

- Deployment of instrumentation to measure plasma, neutrals, magnetic and electric fields and dust particles at the lunar surface.

Implementation approach

Phase 1

In Phase 1, opportunities to deploy neutral and ion spectrometers, plasma instrumentation (e.g. Langmuir probes), magnetometers and dust instrumentation to the surface should be taken to any location. Survival and operation of instruments across the terminator is required. Long duration survival is a goal, requiring the availability of power and thermal support during the lunar night.

Phase 2

In Phase 2, the goal should be to deploy a global network of long lived instrument packages to measure the global exosphere, dust and plasma environments in diverse geographical locations. Such a network could build on earlier deployments. This could be achieved through international coordination, defining standards for instrumentation, measurements, performance, data access and locations for deployment. This could build any deployments achieved during Phase 1, adding to them with new stations and instrumentation.

Phase 3

In Phase 3, a continuation of the network of stations should be enabled to assure continuous measurements at diverse locations and including specific areas of interest and complexity including lunar swirls, magnetic anomalies and the polar regions.

Campaign 5: Near surface geology, geophysics, mineralogy, geochemistry

The lunar surface contains a diversity of geological materials, from rocks formed from the products of planetary differentiation and volcanism, to the fine grained regolith that covers the surface, formed by billions of years of meteoroid impact. The geological settings of these materials and their mineralogical and their geochemical compositions provide insight into the processes that formed them, the history that shaped them and the environment in which they have remained.

In situ measurements with a variety of instrumentation provide information on these materials and the context in which they are found. These investigations can address many scientific objectives and provide a broader context for the more comprehensive examination of returned samples.

A wide variety of potential instrumentation for in situ geological, geochemical and mineralogical investigations has been developed for planetary missions, including those to Mars, and extensive heritage exists in Europe. Instrumentation should be selected based on the specific scientific objectives of a given mission and the boundary conditions of a given opportunity. The priority for in situ investigations of geology, geochemistry and mineralogy is therefore to provide new data from previously unexplored locations, the specific approach should be established based on scientific priorities and locations. Mobility is always a major asset.

Implementation approach

Phase 1

In Phase 1, opportunities to deliver geochemical instrumentation to the lunar surface to new sites, and in particular those identified as being of high priority [e.g. RD8], are favoured. Instrumentation of interest could include imaging systems, instrumentation to measure elemental composition (e.g. x-ray and laser ionisation breakdown spectrometers) or mineralogy (e.g. infrared and Raman spectrometers). Mobility is a benefit if available.

Phase 2

In Phase 2, instrumentation should be deployed on robotic missions with mobility to explore beyond the landing location at high priority landing sites [e.g. RD8] where important objectives for science can be addressed.

Phase 3

In Phase 3, for human missions in situ geological and geochemical information can be gathered by robotic elements in areas that human will not visit, can be used to characterise sites in advance of human activity and can be used to identify sites and samples of interest for human activity and sample return.

Campaign 6: Biological and physiological effects of the lunar environment

Lunar missions would provide the ability to investigate the role of gravity in biological processes, providing a 0.16 g data point between 0 and 1g. Relationships are not likely to be linear with different systems having different curves. Knowledge of long term responsiveness can be attained, as Apollo sojourns were short (3 days max) and largely constrained to the lunar lander with a few EVA's. Currently almost nothing is known about the long term effects of life in partial g.

The transit time was also short during the Apollo missions, whereas future crew may stay in a cis-lunar orbit for extended periods and then land. The interaction between microgravity de-conditioning and partial gravity exposure needs investigating. This maps in part the transition from immobilisation to rehab. In fact provision of prolonged partial gravity rehab might speed neurological rehab, reduce sensitive tissue damage, and minimise risk.

There is currently no understanding of whether 0.16 g is sufficient to maintain physiological system functionality, what effect it may have on crew member functionality, whether decrements reach a plateau, and what strategies would be effective to mitigate de-conditioning. This links to understanding lower metabolic rate effects and devising optimal strategies to counter this without creating weight change swinging.

Extended periods in/on the Moon are vital to build a real understanding of the actual biological sensitivity to the radiation environment of space beyond the Van Allen belt. All current models are fundamentally flawed and in no way allow us to determine real risk, or understand factors that might affect it (e.g. such as age). There is also the need to understand repair mechanisms, where their critical levels are, and how to promote repair systems.

Lunar habitation is vital to develop and mature safe and sustainable in situ resource utilisation systems and truly closed loop life support systems that are vital for Solar System exploration and economic near Earth commercial spaceflight operations. Autonomous medical systems for diagnosis, e.g. autonomous imaging/image processing, non-flow dependent and re-chargeable point-of-care diagnostic systems, differential diagnosis algorithms, autonomous optimal treatment planning and tracking, would have significant Earth applications in remote areas and drive health efficiencies/outcomes. A key driver also is the miniaturisation of systems and multi-flexing of capabilities.

There is also the need to understand in controlled environments non-sunlight entrained sleep when there is partial gravity. Basal metabolic rate will be higher than in microgravity and more similar to low activity individuals, often those with sleep disorders.

Individualised medicine, particularly in terms of optimal pharmaceutical, dose optimisation, and potentially in situ drug manufacture (drug 3d printing) can all be explored. The drive to accurately determine and prolong drug life spans is an area of almost no research on Earth due to the fact that big pharma wants to maximise sales.

Drive research into biological, microbial, viral and fugal response to closed environments where diversity is reduced is important as this maps the general trend on Earth where most organisms are killed by hygiene procedures. Some either have, or develop resistance and then hold a preferential place in the ecosystem leading to new development paths.

Space exploration is a driver for hibernation/torpor/calorie restriction research as methodologies to promote reduced metabolic rate to reduce acute systemic damage, to preserve life during impaired biological health, and to promote early stage healing (i.e. prior to ultimately negative scar tissue infiltration).

Implementation approach

Phase 1

Exposure, return and analysis of biological samples through Missions of Opportunity.

Phase 2

In Phase 2, in situ monitoring of biological samples and in situ testing of key properties of lunar dust through Missions of Opportunity.

Phase 3

Return of pristine lunar dust for in vitro testing on human missions. Research in this area will inform on utilising humans at the lunar surface and the supporting systems that they will bring to perform biological and physiological experiments.

Campaign 7: Physics and astronomy from the Moon

The lunar surface offers a number of opportunities to perform physics and astronomy research. This campaign aims to prepare the way for the use of the Moon for astronomy and physics research in the future and to address some of the simpler opportunities early on.

In the simplest case laser retroreflectors reflecting laser pulses from Earth can be used to test general relativity. This would require the deployment of new laser retroreflectors at the lunar surface at any new locations.

The next activity would be the deployment of a simple tripole radio antenna at the lunar surface and on the lunar far side. This antenna could provide the first measurement of the long wavelength radio emission (2-60MHz) from the heavily red shifted Hydrogen I emission from the cosmic dark ages, several tens of millions of years after the big bang, as well as observing emission from various other cosmic sources. Such an antenna would also characterise the environment and prepare for the eventual deployment of a network of such antennas, forming an interferometer and allowing the first imaging of the sky in long wavelength radio.

Measurements of the dust and seismic environment would support preparations for future optical and infrared observatories.

Implementation approach

Phase 1

In Phase 1, deployment of laser retroreflectors to diverse and geographically dispersed locations at the surface of the Moon should be a priority. Opportunities to deploy a triple radio antenna to receive long wavelength radio at the lunar far side should be taken. Measurements of the natural dynamics of the dust environment should be measured to prepare for future observatories.

Phase 2

Laser retroreflectors should be included as secondary payloads on surface missions and a radio antenna should be deployed at the far side, if not already achieved. A goal should be the deployment of a network of three or more radio antennas at the lunar far side to provide the first low frequency radio images of the sky. A network of dust instruments should be used to characterise the natural lunar dust environment.

Phase 3

Phase 3 should see the deployment of a long wavelength radio astronomy observatory at the lunar far side and preparation of new observational capabilities in various wavelengths.