ENABLING TECHNOLOGIES FOR ACHIEVEMENT OF LUNAR SCIENCE GOALS: A EUROPEAN PERSPECTIVE.
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Background: The Moon is a high priority target for exploration by the world's space agencies [1]. In this context, key lunar science questions have been compiled, discussed, and reviewed by the lunar science community in the course of several major studies. In particular, the American National Research Council (NRC) published a report entitled "Scientific Context for Exploration of the Moon" [2], which has served as a reference for experiment, mission, and strategic planning since its publication in 2007. Recently, the Lunar Exploration and Analysis Group reviewed the progress made on achieving the goals outlined in the NRC report [3], where they retired some goals and added new goals based on the results and questions arising from recent studies and missions. These and other reports and papers (e.g. [4,5]) were used to support the definition of ESA's scientific and technological strategies for the Moon [6,7]. Recently, new white papers were produced for ESA's SciSpacE strategic planning process [8] to summarize the existing documentation and formulate recommendations, particularly for technological capabilities needed for addressing top science goals (Table 1).

Key Enabling Technologies: Key steps for future long-term lunar exploration will require the development of enabling technologies, including: (1) precision landing and automated hazard avoidance, (2) surface mobility, (3) power and heating systems to enable night and PSR survival, (4) tele-robotics, (5) significant (>1000 kg) landed payload masses, (6) deep (10-100m) drilling capability, (7) sample return capability, (8) cryogenic sampling, caching, and return, and (9) development of human operational capabilities in the lunar vicinity and/or on the lunar surface.

This list is not exhaustive, but serves to highlight key areas for technology development as needed to reach the major scientific goals in the next decades (Table 1). We defined short-, mid-, and long-term recommendations for ESA in Table 1 (S, M, L; respectively) for each major scientific theme. The recommendations include participation on international missions, as well as technology development required for scientific progress. Short-term progress can be made in answering fundamental scientific questions about the Moon by leveraging existing technological capabilities and partnerships. Plans for mid- to long-term technology development, including the capabilities listed above, will enable the achievement of higher-level scientific goals. Many of the scientific goals can be accomplished via remote sensing and robotic missions. However, detailed geological studies and refined selection of lunar samples will benefit significantly from the involvement of astronauts, either via tele-robotics in the lunar vicinity or on the lunar surface [9,10]. A station or Gateway in the lunar vicinity could serve as a platform for lunar surface operations, including remote collection and transfer of lunar samples.

Testbed for Destinations Beyond the Moon: A human presence on the Moon will not only allow the dexterous and dynamic collection of samples and measurements for investigation of scientific questions in real-time, but also provide a valuable testbed for technologies that enable exploration of more distant destinations. For example, precision landing and automated hazard avoidance, tele-robotics, and surface mobility improvements can be applied to missions to all solid planetary bodies. Development of cryogenic sample return could be used on missions to comets and icy moons in the outer Solar System. ISRU and lunar construction technologies will serve as a basis for longer term habitation of the Moon and foster a lunar economy to support further research and development [11-13]. Moreover, technological developments in robotics, communications, resource use, and other technologies will feed back to terrestrial applications.

References: [1] ISECG (2017) *Global Exploration Roadmap*. [2] NRC (2007) *Scientific Context for Exploration of the Moon*. [3] LEAG (2017) *Advancing the Science of the Moon*. [4] Crawford et al. (2012) PSS 74, 3-14. [5] Pieters et al. (2018) *Transformative Lunar Science*, SSERVI. [6] ESA (2019a) *ESA Strategy for Science at the Moon*. [7] ESA (2019b) *ESA Space Resources Strategy*. [8] Carter et al. (2021) White Paper #3: Planetary Science https://esamultimedia.esa.int/docs/HRE/03_PhysicalSciences_Planetary_Science.pdf. [9] ISECG (2017) *Scientific opportunities enabled by human exploration beyond low-earth orbit*. [10] Sauro et al. (2023) Acta Astronautica 204, 222-238. [11] Duke et al. (2006) *Development of the Moon*, Rev. Min. Geochem. 60, 597-656. [12] Crawford (2016) Space Policy 37, 58-61. [13] Spudis (2016) *The Value of the Moon: How to Explore, Live and Prosper in Space Using the Moon's Resources*, Smithsonian Books.

Table 1. *Outstanding science questions [e.g., 1-7] with highlighted critical experiments, relevance for human/robotic exploration, and recommendations for ESA activities for short (S), mid- (M), and long (L) term strategic planning.*

Open questions	Experiments	Relevance	Recommendations for ESA
Bombardment in the inner Solar System Ancient: Nature of bombardment on the early Moon? Relation to the emergence of life on Earth? More recent: Understand the nature of bombardment in the last 1 Ga? Present: Present flux?	In situ and/or sample return age analyses for (1) key lunar basins (including South Pole Aitken), (2) young basalts, (3) key young craters Remote observations of newly formed craters, and installation of seismic networks to measure their frequency and magnitude	Present bombardment: Assess present hazard for the Earth and Moon Absolute chronology for the Solar System: Interpretation of geological history of terrestrial planetary bodies, feeds into agency strategy and mission planning Technology driver: Development of communications, landing, payload, and surface operations capability	(S) Participation in Chang'e-5 and Chang'e-6 sample analyses (S) Develop/support implementation of seismic/geophysical payloads (M) In situ analysis payload development, sample return mission or payload development for Argonaut (M-L) At least one in-situ age or sample return mission to a key geological unit (L) Gateway-based, human/robotic sample return concepts
Lunar interior, seismicity, tectonics Formation/ differentiation? Origin of asymmetric thermal/volcanic evolution? Current seismicity?	Globally distributed seismic and heat flow network; expanded retroreflector network	Evaluate present hazard for surface operations/construction Technology driver: Development of communications, landing, payload, and surface operations capability	(S) Develop/support payloads with geophysical instrumentation (S) Support placement of geophysical network nodes at mission of opportunity sites (L) Deploy geophysical network
Geological processes as revealed by the Moon Formation/evolution of crust: Crustal homogeneity (LMO, KREEP etc.)? Volcanism: How recent? Role of volatiles? Thermal evolution? Interior diversity? Resources? Impact cratering: Processes as revealed on a body with less active geology than the Earth?	Sample return and diverse in situ measurements Orbital compositional observations at higher resolutions and extended wavelengths Regional seismic networks Change-detection	Resource assessment for materials applicable to ISRU, construction, and other surface activities Scientific input for agency strategy and mission planning Technology driver: Development of communications, landing, payload, and surface operations capability	(S) Chang'e sample analysis participation (S) Develop/support basic mineralogical/geochemical packages on missions of opportunity (S) Support additional studies of landing sites for agency-directed use during missions of opportunity (M) Remote observation of lunar surface at extended thermal infrared wavelengths (M) Support/develop follow-on mission for NASA's Lunar Reconnaissance Orbiter (M) In situ analysis payload and/or sample return development (L) Gateway-based sample return concepts (L) Collaborate with CNSA on ILRS
Water and other volatiles Origins? Distribution? Abundances? Compositions? Processes? Lunar volatile cycles ? Resources?	Orbital observations and ground truth of nature, distribution, extent, composition of water and volatiles Cores to investigate vertical distribution and nature Cryogenic sample return	Resource assessment for materials applicable to ISRU, construction, and other surface activities Technology driver: Development of communications, landing, payload, and surface operations capability; Development of ice/volatile handling and storage	(S/M) PROSPECT on CLPS and other CLPS opportunities (M) Support delivery of analytical/technical payloads to polar regions (M) Orbital mapping of H_2O ice and other species at higher resolution (M) ESA Argonaut payloads (L) Cryogenic sample return; multiple drill cores (L) Gateway-based sample return concepts (L) Collaborate with CNSA on ILRS
Regolith Formation and weathering processes? History of the Sun and Solar System? Resources?	Sample return, regolith stratigraphy/deep drill core, samples of paleoregolith; swirls	Resource assessment for materials applicable to ISRU, construction, etc. Technology driver: Development of communications, landing, payload, and surface operations capability, and deep-drilling technologies	(S) Chang'e sample analysis participation (S) Participation in ANGSA (S) Develop/support placement of basic mineralogical/geochemical/geotechnical packages on missions of opportunity (M) ESA Argonaut payloads (M/L) Return of cores and paleoregolith (L) Gateway-based concepts
Atmosphere, dust, and plasma environment Exosphere formation/evolution? Dust levitation and transport? Sources/migration hydroxyl and water? Changes due to activities?	UV and mass spectrometers, material adhesion experiments, Langmuir probes	Assess hazards for future robotic and human exploration	(S) Develop/support placement of plasma, neutrals, magnetic and electric fields and dust particles instruments (M-L) Deploy a global network of long term monitoring stations
Moon as a platform Astronomy, astrophysics, fundamental physics, life sciences and astrobiology	LF radio-antennas, optical/IR telescopes, laser retroreflectors, CR and radiation detectors; environmental effects on humans	Prepare for long-term human habitation of the Moon and human missions to Mars and beyond	(S) Deploy laser reflectors (M-L) Deploy LF radio antennae, cosmic ray detectors, Earth-observing instruments, life sciences experiments (L) Gateway-based, human/robotic concepts; habitation studies