NASA/TM–20220017053
NESC-RP-22-01729

Unique Science from the Moon in the Artemis Era

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November 2022

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November 2022

Acknowledgments

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NASA Engineering and Safety Center
Technical Assessment Report

Unique Science from the Moon in the Artemis Era

October 20, 2022

Report Approval and Revision History

NOTE: This document was approved at the October 20, 2022, NRB.

Approved: TIMMY WILSON Digitally signed by TIMMY WILSON Date: 2022.11.04 09:18:30 -04'00'

NESC Director

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Azita Valinia, NESC Chief Scientist, GSFC	10/20/2022

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Technical Assessment Report

1.0 Notification and Authorization

Since the beginning of the space age, the Moon has been proposed as a platform for astronomy. The Moon provides unique capabilities for astrophysics observations. NASA's Artemis plan to return humans to the Moon in the mid-2020s in a sustainable manner provides an opportunity to advance synergistic approaches between human and robotic exploration. This NASA Engineering and Safety Center (NESC) workshop assesses the feasibility and value proposition of using the Moon as a location for performing unique science observations, leveraging Artemis-era infrastructure while evaluating risks and key engineering challenges.

Azita Valinia, NESC Chief Scientist, was assigned the lead for this assessment. The key stakeholders for this assessment include the Science Mission Directorate (SMD), the Space Technology Mission Directorate (STMD), the Exploration Systems Development Mission Directorate (ESDMD), and the Space Operations Mission Directorate (SOMD).

2.0 Signatures

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Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

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3.1 Acknowledgments

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The NESC workshop was conducted in hybrid mode at NASA Kennedy Space Center and online. More than 400 registrants attended the workshop. This group photo captures the in-person attendees on June 8, 2022.

4.0 Executive Summary

> **“A program of scientific exploration can be constructed this decade whereby science enables human exploration and human exploration enables science.”**
>
> *From Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*

Since the beginning of the space age, the Moon has been proposed as a platform for astronomical facilities. With the NASA Artemis plan to return humans to the lunar surface in the mid-2020s, there is renewed interest in using the Moon as a location for studies ranging from observing our solar system to studying the early universe before the first stars were formed. Great opportunities lie ahead to advance groundbreaking science using the synergy between human and robotic exploration. Furthermore, *human exploration that does not include science as one of the primary objectives is a missed opportunity and is likely to result in the exploration program not being sustainable.* For these reasons, a workshop bringing together the various stakeholders was sponsored by the NASA Engineering and Safety Center (NESC) on June 7–9, 2022, to accomplish the following:

- Explore leveraging the Artemis era infrastructure to conduct unique science experiments and observations from the lunar surface and maximize return on investments.
- Advance synergistic approaches between human and robotic exploration.
- Identify and address key engineering challenges and risks.

The NESC workshop produced the following deliverables: 1) unique and compelling science case studies that can be accomplished from the surface of the Moon, 2) synergistic approaches for human/robotic science exploration, 3) lunar science exploration engineering challenges and approaches for risk mitigation, and 4) methodologies for defining Artemis mission requirements for decadal-level science studies.

For the purposes of this assessment, the workshop identified three case studies to place a low-frequency radio telescope on the lunar far side to study the Dark Ages[1] of the Universe. These were chosen because this low-frequency radio band can only be observed from space, with the Moon’s far side shielding radio interference from the Earth. Additionally, the decadal survey on Astronomy and Astrophysics 2020 (Astro2020) identified the science topic as a future area of discovery. In addition, NASA funding has previously been applied to evaluate the feasibility of these concepts. This is not an endorsement of their priority relative to other possibilities—that is the role of the decadal surveys and peer review. These case studies are not exclusive, and there are many others that NASA can consider.

The key findings, observations, and NESC recommendations from the workshop are as follows.

- ➢ Future science decadal surveys should consider use of human exploration capabilities as viable options for meeting decadal-level science objectives.

Priorities for NASA science goals and missions for each NASA science discipline are set by decadal surveys administered by the National Academy of Sciences (NAS). Realizing the use of

---

[1] The Dark Ages is the epoch in the Universe before the first stars were born.

the Moon as a science platform will require high-priority science and mission endorsements as identified in future decadal surveys. *A key element of this NESC assessment is to identify how the human exploration program can be leveraged to achieve decadal-level science.* There are previous successful examples of this, with the most spectacular being the Space Shuttle launch of the Hubble Space Telescope (HST) and subsequent HST servicing missions. More recently, this leveraging has been limited primarily to telescopes and facilities attached to the International Space Station (ISS) via Principal Investigator (PI) led and directed opportunities. For a future lunar base camp, there are analogies with the Amundsen-Scott South Pole Station in Antarctica, which provides a hub for scientific activities, including telescopes to study the cosmic microwave background and neutrino experiments. *Making science a key part of the Artemis goals provides a long-term sustaining purpose beyond just exploration for its own sake.*

- All future science decadal surveys should request briefings from NASA on the current status of the Artemis architecture and the overall Moon to Mars strategy in a public forum so that viable mission concepts can be discussed and proposed.

Exploiting the infrastructure provided by the human exploration program will have major benefits both in cost savings to the science program and its sustainability (e.g., via potential upgrades/repairs of facilities). There is concern from the science community that the changing programmatic goals and funding uncertainties in the human exploration program make dependencies risky. On the other hand, as demonstrated by HST and the ISS, the potential exists for achievement of major decadal-level science when the human and science programs work together. To convince future decadal surveys that scientifically exciting, technically feasible, and cost competitive scenarios exist, it is critical to define key parameters such as down-mass (to the lunar surface), available volume, and communication interfaces for possible scientific investigations. To prepare for future decadal surveys, this definition should begin as soon as possible.

- Beyond Artemis IV, the Science Mission Directorate (SMD) and the Exploration Systems Development Mission Directorate (ESDMD) should continue to be empowered to collaboratively identify mission requirements to accomplish decadal-level science via human exploration missions.

As highlighted by the 2022 planetary decadal survey, there is a risk of science falling between the directorate stovepipes at NASA HQ. Currently, the science requirements are retrofitted to the capabilities of the early Artemis missions. This is understandable given that early missions are to demonstrate basic capabilities, but this limits the science return. Just as the later Apollo missions made science a driving goal with increased capabilities, the same should be true for Artemis. This must bridge HQ mission directorates, with clear lines of authority and accountability for the science payloads leading back to SMD. This can be captured with an upfront SMD-led science definition team process for both large strategic observatories and consideration of the requirements for more modest PI-led opportunities. What is critical is that architectural elements to enable decadal-level science be included in the Artemis requirements at an early stage of the Artemis Program. SMD must have both responsibility and authority; otherwise, new and bold ideas are liable to remain unrealized.

- To enable in-space servicing, assembly, and manufacturing (ISAM[2]), design of future observatories or instruments deployed on the lunar surface should follow the HST and ISS models, where standards are followed to make them astronaut friendly for servicing (e.g., standard bolt sizes, easily accessible avionics, avoidance of sharp edges, etc.).

Any human assembly of scientific instruments or observatories on the lunar surface should focus on items that cannot be affordably and technically implemented by robots. For situations where robotic exploration is not feasible and affordable, *the presence of humans on the lunar surface is an opportunity to deploy, repair, and upgrade scientific instruments or observatories.* This includes those that may have been robotically landed and deployed or those that have been manufactured *in situ*. The lesson learned from HST and the ISS is that creating and following standards (e.g., using the same bolt sizes and accessible connectors, and providing easy access) is crucial. This provides the ability to recover from unexpected events and failures and upgrade existing facilities with new technology, thereby ensuring sustainability.

- While the lunar surface environment is challenging, with dust contamination and maintaining a far-side radio quiet zone being the major concerns, no showstoppers to using the Moon as a platform for science observatories were identified.

The lunar surface is a challenging environment with dust contamination, large thermal swings, extreme shadows at the lunar poles, and the need for power generation and storage. Of these, dust contamination of optics has been a driving concern for astronomical facilities. The successful operations of ultraviolet (UV) telescopes on the lunar surface by Apollo 17 astronauts and, more recently, robotically on the Chinese Chang'e 3 mission for several years have demonstrated basic feasibility for optical facilities. Dust is not an issue for radio telescope performance, but radio frequency interference (RFI) is a concern. While the frequencies being observed are lower than typically used for spacecraft communications, the major concern arises with broadband radio emitters (e.g., high-power switching circuits, motors, and digital noise from computers). Adequate low-frequency RFI testing, screening, and shielding must be considered and standardized for all spacecraft and payloads that will be visible from the lunar radio quiet zone. In the near term, payloads that demonstrate needed technical capabilities and/or the scientific potential of the lunar surface as a platform for frontier astrophysics should be encouraged for development and deployment[3]. Site assessment is among the first tasks in establishing a terrestrial telescope facility, and the same should be true for the lunar surface.

In summary, to ensure sustainability of the human exploration program and provide added return on investment, *integration of decadal-level science requirements into the Artemis Program at an early stage is a must.* Otherwise, it is likely that a lunar human exploration program will not be sustainable.

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[2] In-space Servicing, Assembly, and Manufacturing National Strategy (https://www.whitehouse.gov/wp-content/uploads/2022/04/04-2022-ISAM-National-Strategy-Final.pdf).

[3] Consistent with NASA's Moon to Mars Objective PPS-1, "Conduct astrophysics and fundamental physics investigations of space and time from the radio quiet environment of the lunar far side," available at https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf.

5.0 Workshop Motivation and Structure

NASA is planning to return astronauts to the Moon, followed by journeys to Mars. This time, astronauts will remain on the surface of the Moon for long periods of time, developing a base camp and infrastructure for continued exploration of the Moon, which can be used as a stepping stone to Mars. Hence, it is timely to examine the feasibility and value proposition of using the Moon as a platform for scientific exploration.

Lunar surface science exploration and resource utilization have been topics of several recent NASA Lunar Surface Science Workshops (LSSWs). These workshops have been focused on near-term Artemis missions and scientific exploration objectives centered on lunar geology and resources. *This NESC workshop, however, focused on longer-term science exploration objectives using the Moon as a platform for unique scientific exploration.* A prominent example of such science is low-frequency radio astronomy observations from the far side of the Moon, a band that is not accessible from the Earth's surface or its orbit. Assembling radio observatories on the far side of the Moon is a complicated feat that will require human and robotic collaboration and potentially *in-situ* resource utilization, while leveraging lunar surface infrastructure that is planned to be built on the surface of the Moon. This effort will require at least a decade or more of planning and technology and engineering research and development to bring the concepts to reality. Close collaboration will be required between scientists, engineers, technologists, and the spaceflight operation communities to develop and plan concepts of operations (ConOps) for unique scientific exploration goals in the next decades. This workshop was conceived as a first step toward that goal.

The workshop primarily considered revealing the Dark Ages of the Universe, before stars and galaxies formed, by observing the highly redshifted 21-cm line of neutral hydrogen using a radio telescope on the far side of the Moon as the leading unique science, which can be enabled only from the Moon. This science was identified as an area of "discovery" in the Astro2020 decadal survey, where innovative approaches to obtaining these measurements will certainly lead to breakthrough science discoveries in cosmology. Three concept studies were explored to understand the benefits of and interactions between robotics, Artemis infrastructure, and human extravehicular activity (EVA) to bring the concepts to reality and sustain them for many years. These concept studies are outlined in Section 6.

The workshop participants examined key engineering challenges and risks for science experiments from the Moon. These included lunar dust and charging, communication, power generation, extreme thermal environments, and lighting. Engineering challenges and risks are summarized in Section 7.

Finally, through a number of interdisciplinary interactive sessions, the workshop participants sketched a framework for synergistic science and human exploration activities that provides precursor requirements for bringing complicated scientific experiments from the Moon to reality in the 2030s and 2040s. These are summarized in Section 8. Section 9 summarizes the findings, observations, and recommendations from the workshop. A list of workshop participants is included in Appendix A, and the workshop agenda is provided in Appendix B.

6.0 The Lunar Surface as a Platform for High-priority Decadal Science

6.1 Lunar Surface Observatories: Past and Present Experience

Ultraviolet imaging and spectroscopy of astrophysical targets from the lunar surface were demonstrated by the Far-Ultraviolet Camera/Spectrograph deployed during Apollo 16 (see Figure 6.1-1) [Carruthers, 1973]. Hence, a proof of concept was established in NASA's initial wave of lunar exploration for conducting up-looking observations from the Moon with the presence of astronauts on the lunar surface. Carruthers [1973] remarks on "the great potential of the lunar surface as a base for astronomical observations."

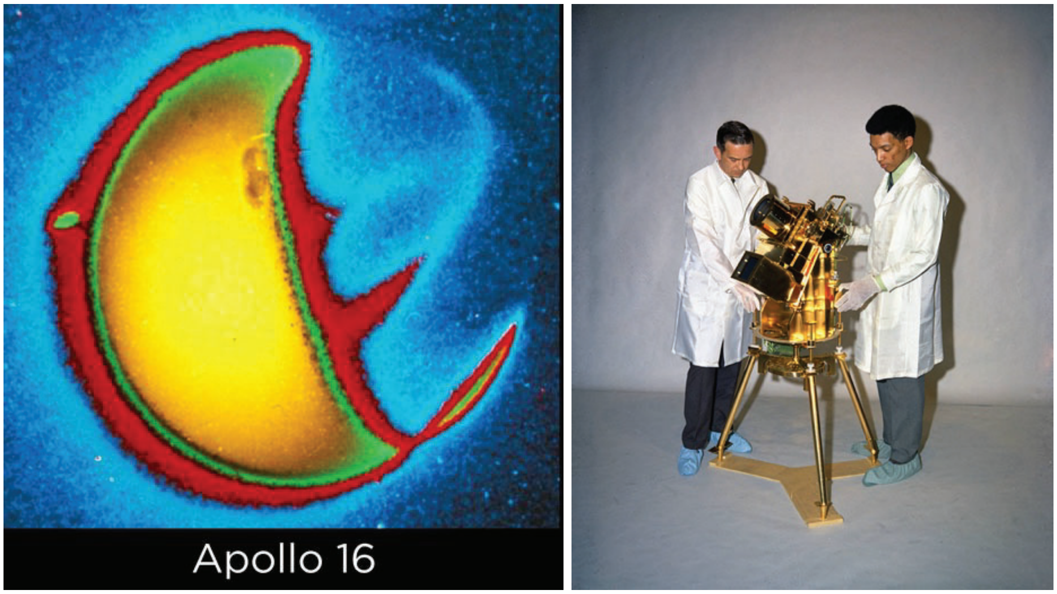

Figure 6.1-1. First View of Earth in Far UV Light (left) using UV Telescope (right)
In the photograph on the right, PI Carruthers is shown (right) with a technician (left). The image on the left was taken from the lunar surface during Apollo 16 by John Young and Charles Duke.

Other than pictures taken by the astronauts during the Apollo missions, ranging measurements using the Apollo laser retroreflectors, and the Carruthers tripod-mounted UV camera on Apollo 16, the U.S. has not executed an up-looking telescopic observing campaign *from* the lunar surface. The Chinese, however, demonstrated sustained lunar surface scientific operations on their Chang'e 3 and 4 robotic missions using a repeating sequence of lunar day operations and lunar night hibernation. The Chang'e 3 mission hosted a 130-millimeter (mm) diameter gimbaled Lunar-based Ultraviolet Telescope (LUT) that operated during lunar daytime for 2+ years using a commercially available charge-coupled device (CCD) detector, employing simple dust mitigation protocols, and showing no degradation of optical performance over the mission lifetime [Wang et al., 2015]. Those protocols included keeping the telescope optics stowed or covered during launch and landing and stowing the telescope prior to the day-night transition and reopening after the night-day transition.

The Moon has a tenuous dusty exosphere that has been observed in various ways, including by the Lunar Dust Experiment aboard NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission (e.g., [Elphic et al., 2015; Horanyi et al., 2016]). A persistent, albeit extremely thin, cloud of ballistic dust surrounds the Moon, fed by micrometeoroid impacts on the lunar surface. Close to the surface, the densities are estimated to be a few particles per cubic meter, which would not impact a SmallSat-scale experiment operating for weeks, months, or several years. However, over time the settling of dust on optical surfaces may impede their long-term throughput and affect precision optical measurements and interferometric instruments. An analysis by Murphy et al. [2010] suggests that over several decades, lunar dust has accumulated on exposed optical surfaces of the lunar retroreflectors left by the Apollo astronauts. Over four decades, this has gradually degraded the return signal strength by an order of magnitude (that is not to say that the reflectors have become opaque, but they are very sensitive to thermal gradients, and warming due to accumulated dust is the simplest explanation for the degradation). Thus, future lunar surface-based telescopes will need to include a dust mitigation strategy (e.g., aperture covers such as those used by free-flying observatories like the HST, Spitzer, and Kepler; stowing; baffling; defining Sun avoidance angles as needed with free-flying satellites; or optical surface cleaning procedures).

To provide further demonstration of imaging from the lunar surface, a small, up-looking camera sponsored by the International Lunar Observatory Association (ILOA) and built by Toronto-based Canadensys Aerospace, called ILO-X, is planned for the first Intuitive Machines Commercial Lunar Payload Services (CLPS) mission (IM-1), currently scheduled to be launched in late 2022. Meanwhile, the NASA STMD is supporting efforts to remove or repel lunar dust from surfaces including optical systems [NASA BIG Idea Challenge Press Release, 2021].

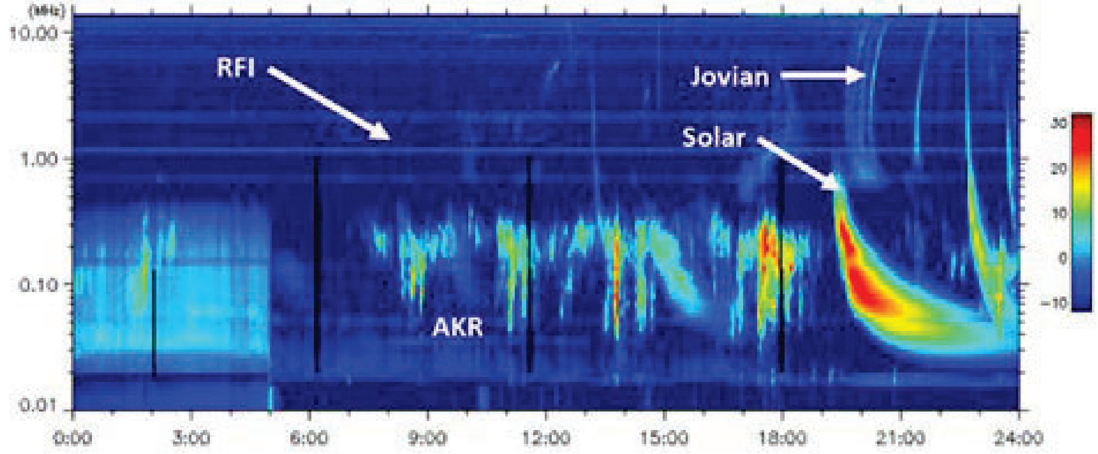

Figure 6.1-2. Low-frequency Radio Spectrum Measurement by RAE-2 (imaging geospace from the Moon)

NASA’s Radio Astronomy Explorer-2 (RAE-2) (Explorer 49) satellite made the first radio astronomy observations in lunar orbit in 1973–1975. RAE-2 was placed around the Moon to shield the satellite from the Earth’s auroral kilometric radiation (AKR), >40 dB, which is brighter than the Galaxy below ~1 megahertz (MHz) [Alexander et al. 1975]. RAE-2 focused on low radio frequency measurements of the Milky Way, solar and Jovian radio bursts (Figure 6.1-2), the AKR originating from the terrestrial magnetic field, and the extragalactic radio background. The Chang’e 4 mission was the first to place a lander on the lunar far side. It housed a Very Low Frequency Radio Spectrometer and a tri-pole antenna operating between 0.1 and 40 MHz [Chen et al. 2019] with science goals to observe solar radio bursts during the lunar day and measure the lunar ionosphere at its surface. These have been the foundational observations that have led to considerations for putting a radio observatory on the lunar far side, shielded from human RFI and AKR.

6.2 Setting Science Priorities

Decadal surveys are used by NASA to set both scientific priorities and the missions to address them. This consensus process, administered by the NAS, covers each science division within the NASA SMD. The recent Planetary Decadal Survey released in May 2022 included examining the possible science that could be leveraged by the return to the lunar surface. Key recommendations (in the context of lunar science) included:

- Conducting decadal-level science should be a central requirement of the human exploration program.
- NASA should engage with the science community to 1) define scientific goals for its human exploration programs at the early stages of program planning; and 2) ensure scientific expertise in field geology, planetary science, and astrobiology in its astronaut teams.

The survey results further note that “The separation of roles and responsibilities across multiple Divisions and offices therein is not conducive to the development or implementation of a cohesive lunar science and exploration program.”

Ultimately, for the lunar surface to be used for scientific observations, both the science goals and the mission implementation must be highly ranked in a decadal survey. The recent Astro2020 decadal survey report released in November 2021 did not prioritize any observatories that use the Moon as a platform.

O-1. Exploration that does not include science as one of the primary objectives is a lost opportunity and likely to mean the exploration program is not sustainable.

F-1. Realizing use of the Moon as a platform for science will require high-priority science and mission endorsements from future decadal surveys.

Many in the space and Earth science community have concerns about relying on the human exploration program to realize strategic missions. These concerns include fear of cancellation, the costs of human rating for an instrument or observatory, and programmatic delays and associated costs increases. For example, after the loss of the *Challenger* space shuttle in 1986, observatories that were originally planned to be launched or serviced by the space shuttle were moved to expendable launch vehicles and/or launched to orbits where they could no longer be reached by the shuttle for servicing. These included the Chandra X-ray Observatory, the Spitzer Space Telescope, and the Cosmic Background Explorer (COBE) mission. This required major redesign efforts, delays, cost increases, and lost opportunities for upgrading via servicing. The result is NASA space and Earth science programs that are currently decoupled from the human spaceflight programs.

O-2. While there have been notable successes (e.g., HST, ISS), the scientific community is wary of engaging human exploration capabilities because of past changes in destinations, shifting priorities, and delays.

However, there have been examples of successful collaboration in the past, such as the HST (Figure 6.2-1). This was a successful partnership between NASA human spaceflight and science programs. The science program funded the observatory and instruments ($14B), and the human spaceflight program funded launch and servicing missions ($6B).[4] The servicing capability provided ability to recover from unexpected challenges, perform complex repair tasks, and install new state-of-the-art scientific instruments. It is this last capability that has enabled the HST to continue to make discoveries at the leading edge of astrophysics over several decades of operation.

Figure 6.2-1. HST Being Serviced by Astronauts

The ISS provides another example of a successful partnership, although it came following a slow start. Science was enabled on the ISS through the use of exterior payload attach points viewing up (astrophysics) and down (Earth science)[5] and biological and physical sciences (BPS) enabled via onboard experiments. Figure 6.2-2 shows the Neutron Star Interior Composition ExploreR (NICER) telescope on the ISS, which enabled ground-breaking discoveries that led to the winning of the Rossi Prize for the NICER science team. Again, human spaceflight provided the launch and enabling infrastructure, and science funded the instruments via competed (e.g., the Explorers Missions of Opportunity, Earth Venture) or directed opportunities. Other agencies also provided attached payloads, including the funded Alpha Magnetic Spectrometer (AMS), an international collaboration involving 44 institutions from America, Europe, and Asia sponsored by the US DOE and NASA, and the Japan Aerospace Exploration Agency (JAXA)-funded Monitor of All-sky X-ray Image (MAXI) experiment.

Future NASA SMD-funded lunar observatories/instruments are more likely to happen through partnerships between human spaceflight and science programs, following the successful HST/ISS model where the human spaceflight program funds the launch and any human-assisted construction, communications, and servicing, while the science program funds the observatory,

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[4] Fiscal year 2017 dollars [Gainor, 2021].

[5] BPS experiments at the time were being funded by the NASA Human Exploration Directorate.

instruments, operations, and data analysis. Agreements and plans must be in place for future decadal surveys to convince science communities that the opportunity is robust and cost effective.

O-3. Science investigations of decadal-level quality must be a critical part of a sustained lunar presence and preparation for future Mars missions.

R-1. All future decadal surveys should request briefings from NASA on the current status of the Artemis archietecture and the overall Moon to Mars strategy in a public forum so that viable mission concepts can be discussed and proposed.

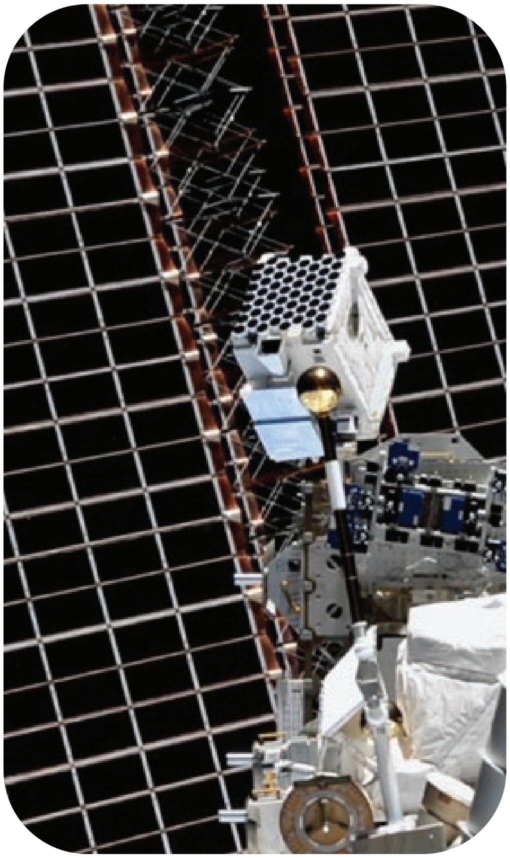


Figure 6.2-2. NICER X-ray Telescope on ISS

6.3 The Promise of Artemis: Sustainable Scientific Exploration from the Moon

The Artemis Program is the Agency's plan to return humans to the Moon. Scientific objectives for the Artemis human exploration program, driven by both U.S. and international science community priorities, are laid out in the Agency's Artemis Plan [Artemis Plan, 2020]:

- Understanding planetary processes.
- Understanding the character and origin of lunar volatiles.
- Interpreting the impact history of the Earth/Moon system.
- Revealing the record of the ancient sun and our astronomical environment.

- Observing the universe and the local space environment from a unique location.
- Conducting experimental science in the lunar environment.
- Investigating and mitigating exploration risks.

NASA's implementation strategy to achieve these objectives focuses on the development of science payloads and enabling technology, the utilization of new human exploration systems (e.g., Gateway and the Human Landing System (HLS)), and science planning for Artemis crews on the Moon specific to the landing site and architectural constraints of each surface mission.

As an example of that process, SMD chartered a Science Definition Team to define compelling and executable science objectives for the Artemis III mission, the first human mission to the surface of the Moon in the 21st century. The process focused on assessing goals for the mission to achieve the science objectives articulated by NASA (above), including investigation approaches, key surface science activities, and potential inputs to the ConOps. Science investigations were drawn from guiding documents like the Lunar Exploration Roadmap [Lunar Exploration Analysis Group, 2016], the Scientific Context for Exploration (SCEM) report and its recent progress report [National Research Council, 2007; Lunar Exploration Analysis Group, 2018], and the Planetary Decadal Survey [National Research Council, 2011, current at the time], as well as white papers solicited from the scientific community [Lunar and Planetary Institute, 2022]. The final report [Artemis III Science Definition Team, 2020] recommends a notional program that captures the highest-priority science for Artemis III and provides the greatest feed-forward to follow-on missions. Prioritization was determined ranking each investigation according to two independent criteria: 1) the compelling nature of the science (e.g., how fundamental the investigation is to making a significant scientific advancement), and 2) whether Artemis III presents an enabling opportunity given the architectural constraints of the mission.

After Artemis III, the Agency's plan is "to conduct operations on and around the Moon that help prepare us for the mission durations and activities that we will experience during the first human mission to Mars, while also emplacing and building the infrastructure, systems, and robotic missions that can enable a sustained lunar surface presence" [Artemis Plan, 2020]. To do this, NASA will develop the Artemis Base Camp (ABC) at the South Pole of the Moon. There are analogies with the Amundsen-Scott South Pole Station in Antarctica, which supports telescopes to study the cosmic microwave background and neutrino experiments in an extreme environment.

This workshop focused on forming a vision for sustainable science under Objective 5: Observing the universe and the local space environment from a unique location, namely, the surface of the Moon. The Artemis Program, both its robotic (CLPS) and human elements, offers substantial opportunities to perform science investigations on the lunar surface that significantly advance decadal science priorities.

6.4 Example Science Opportunities

6.4.1 The Dark Ages

The 21-cm line of neutral hydrogen (HI) offers the only observational probe of the Universe's "Dark Ages," the period of cosmic history before the formation of the first stars; however, this technique requires observations at wavelengths longer than the cutoff of Earth's ionosphere, necessitating a mission in space. Recently, the Astro2020 decadal survey report stated that "At the end of the Dark Ages, the neutral hydrogen pervading the universe became visible against the

CMB [cosmic microwave background] backlight, enabling observations of the primordial density fluctuations over a vastly larger range of scales than for any other cosmological probe…21 cm and molecular line intensity mapping of the Dark Ages and reionization era is both the discovery area for the next decade and as the likely future technique for measuring the initial conditions of the universe in the decades to follow."

HI can be detected through its hyperfine 21-cm transition (λ_{rest}). The observed wavelength of the line (λ_{obs}) grows through cosmological redshifting ($\lambda_{\mathrm{obs}} = (1 + z)\lambda_{\mathrm{rest}}$, where z is the redshift); 21-cm emission from the cosmic Dark Ages ($z \gtrsim 30$) is detected at decameter wavelengths or frequencies of 1 to 50 MHz today. Measuring the signature over a wide range of wavelengths enables a three-dimensional reconstruction of the distribution of matter (since redshift maps to distance). The ultimate deliverable of HI cosmology is, therefore, a tomographic map tracing the evolution of the Universe stretching from before the birth of the first stars through the early Cosmic Dawn epoch. The Dark Ages and the earliest portion of the Cosmic Dawn are only accessible from space based observatories such as the lunar far side at frequencies <50 MHz, whereas the Epoch of Reionization (EoR) may be probed using ground-based arrays (e.g., Low Frequency Array (LOFAR), Murchison Widefield Array (MWA), Hydrogen Epoch of Reionization Array (HERA), and Square Kilometre Array (SKA)).

Figure 6.4.1-1 places these epochs into perspective. After the Big Bang, the Universe was hot, dense, and nearly homogeneous. As the Universe expanded, the material cooled, condensing after ~400,000 years (z~1100) into neutral atoms, freeing the cosmic microwave background (CMB) photons. The baryonic content during this pre-stellar Dark Ages consisted primarily of HI. About 50 million years later, gravity propelled the formation of the first luminous objects—stars, black holes, and galaxies—which ended the Dark Ages and commenced the Cosmic Dawn [Loeb and Furlanetto, 2013]. These first stars (Population (Pop) III, nearly metal-free, ~100 $M_{\odot}$) likely differed dramatically from stars we see nearby, as they formed in vastly different environments [Abel et al., 2002].

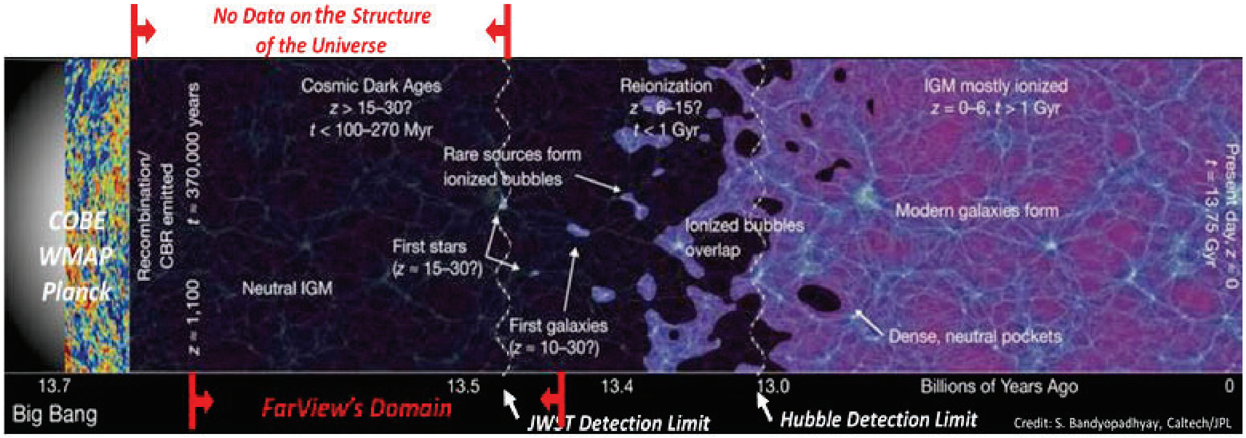


Figure 6.4.1-1. Pre-stellar (Dark Ages), First Stars (Cosmic Dawn), and Reionization Epochs of Universe [reprinted from Bandyopadhyay et al., 2021a]
(These can be uniquely probed using a redshifted 21-cm signal. This history is accessible via the neutral hydrogen spin-flip background. Lunar radio arrays such as FarView will fill in the missing data during the Cosmic Dark Ages and Cosmic Dawn.)

Spatial fluctuations in the 21-cm Dark Ages signal are governed almost entirely by well-understood linear structure formation—the same physics used to interpret observations of the

CMB—allowing precise predictions of the expected signal within the standard cosmological model. Interferometric measurements of fluctuations in the 21-cm Dark Ages signal can therefore uniquely test the standard cosmological model in an unexplored epoch at the onset of structure formation, without the complication of highly nonlinear baryonic effects. Any departure from these well-constrained predictions will provide new insights on the physics of structure formation, potentially into the nature of dark matter [Slayter, 2013], early dark energy [Hill and Baxter, 2018], or any exotic physics [Clark et al., 2018]. Such observations could also measure the ultimate number of linear modes (Fourier modes of three-dimensional density fields) in the Universe and lead to exquisite cosmological constraints, including the masses of neutrinos and their hierarchy [Mao et al., 2008], the non-Gaussianity of initial density perturbation [Muñoz et al. 2015], and the imprints of primordial gravitational waves to reveal the complexity and energy scale of cosmic inflation [Book et al., 2012; Ansari et al., 2018].

In many ways, spatial fluctuations in the 21-cm absorption during the Dark Ages provide the ultimate cosmological observable. The simplest way to quantify these fluctuations is with the power spectrum (Figure 6.4.1-2), which characterizes the amplitude of the variations as a function of spatial scale (1/k), analogous to Planck measurements of the CMB. During this time, the 21-cm line traces the cosmic density field, allowing a straightforward interpretation of the measurement in terms of the fundamental parameters of our Universe [Lewis and Challinor, 2007]. The lack of luminous astrophysical sources makes the Dark Ages signal a clean, powerful cosmological probe and renders the 21-cm line the only observable signal from this era. Note that the power spectrum can only be measured with interferometers where a large range of angular scales can be sampled, in contrast to a large, single-dish telescope.

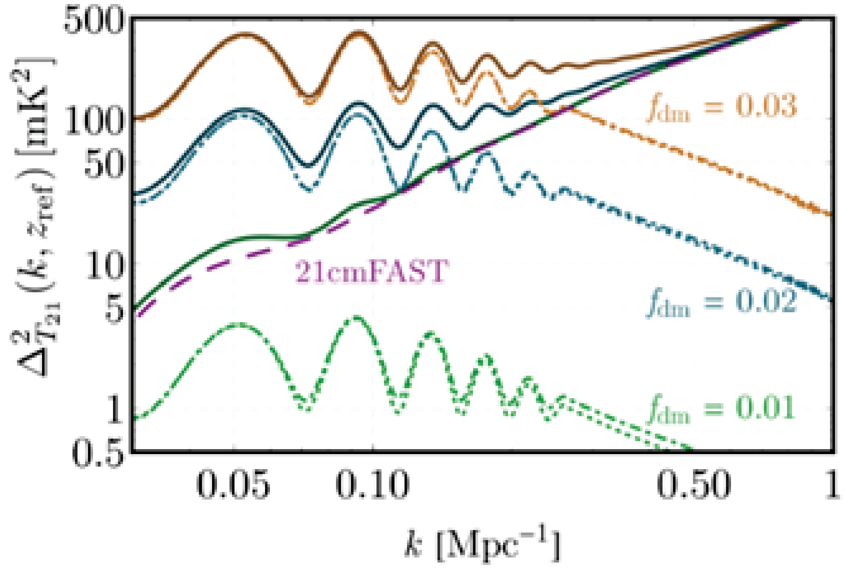


Figure 6.4.1-2. 21-cm Power Spectrum, distinguishing between Different Exotic Physics Scenarios during the Dark Ages

In these models, a fraction f_{dm} of the dark matter is assumed to have a small charge; the oscillations in the power spectrum arise from the large-scale streaming of baryons relative to dark matter. The solid curves are the total power for each value of f_{dm} after linearly adding the dash-dotted lines, showing the contributions from dark matter/baryon scattering to the standard cosmological model (labeled "21cmFAST") [reprinted from Muñoz et al., 2018].

6.4.2 Heliophysics

The Moon is immersed in a plasma environment—the local cosmos—that is "magnetized." It is threaded with magnetic fields that are often "frozen" into the plasma, a state of high electrical conductivity that effectively couples the motions of the plasma and the magnetic field. This inherently strong coupling means that the structure and evolution of magnetic fields (of the Sun, of the Earth, and even of the Moon itself) play an essential role in organizing and regulating the local environment of the Moon—the environment to be experienced by our explorers. By working to understand, and so predict, the variations that occur from day to day and from region to region, the productivity and overall success of future lunar robotic and crewed missions can be significantly enhanced. The most interesting challenge of the lunar plasma-field environment is that it is alternately dominated by the extended but variable outer atmosphere (the "magnetosphere") of the Earth and by the extended but highly variable atmosphere of the Sun (the "heliosphere"). The Moon spends nearly 25% of its orbital period immersed within the Earth's magnetosphere, which offers some degree of shielding from heliospheric effects; the remaining time is spent exposed to the full effects of the Sun's radiation and interplanetary fields. Thus, the lunar plasma environment offers unique opportunities to study a variety of fundamental plasma physics processes—processes that have applications to many other objects throughout the universe.

Since the inception of the U.S. space program with Explorer 1 through present-day space weather missions, scientists in the heliophysics community have worked to develop a thorough understanding of the connected Sun/Earth/Moon system. A great deal more is known about our space environment than was known during the Apollo era, and this new knowledge is ready to be applied. Data from heliophysics missions, past and present, can be mined for applicable measurements. Our understanding of underlying physical processes can be used to provide an informed predictive capability that will aid in the operational planning for lunar and, eventually, Mars missions. The Heliophysics System Observatory (HSO), an ensemble of spacecraft designed to provide system measurements of the Sun/Earth/heliosphere system, is available to provide real-time space weather awareness during crewed flights. And, once a human presence on the Moon is established, new classes of experiments can be implemented to further advance these fields of study.

In the quest to understand our space environment, the first challenge is to understand the basic physics behind the plasma processes of magnetic reconnection, the mass loading of solar and stellar winds, and plasma/dust interactions. These processes play fundamental roles in the explosive processes at the Sun and in planetary accretion. Increasingly, as we probe more deeply into the underlying plasma-field interactions, heliophysicists are guided by comparisons of plasma processes in the Earth's magnetosphere, in the solar corona, in the magnetospheres of other bodies in the solar system (i.e., the Moon and planets), and in distant astrophysical environments. This comparative approach creates a rich variety of unique opportunities for lunar-based heliophysics science. These areas of interest exploit the Moon's unique magnetodynamic environment:

- The Moon has weak crustal magnetic fields, the origin of which is still a mystery and a central question for the science of the Moon. These weak magnetic fields continually interact with the solar wind and lunar dust close to the lunar surface. The presence of weak magnetic fields is common to many planetary bodies, including Mars. On the Moon, however, the locations of these small-scale interactions can be identified precisely and studied near the lunar surface. This is a unique circumstance that will provide new insights into the fundamental behavior of magnetodynamic systems and may hold lessons for models of magnetic fields in the Sun's corona, Earth's magnetosphere, and other planetary systems.

- As the Moon orbits the Earth, it passes through a rich variety of plasma environments that offer the opportunity to study plasma physics processes over a wide range of ambient conditions.
- Mass loading is a term describing the basic plasma process, where bodies such as comets, planets, and moons produce dust and charged particles that become entrained in the impinging solar wind. The products of such interactions and their effects on the solar wind and other astrophysical or planetary plasmas are often observed. The lunar surface offers a unique location in which to study this process as it begins. These studies will contribute to many areas in space science and astrophysics, where the interactions with plasmas, dust, and charged particles play a central role.
- Understanding the interaction of submicron lunar dust grains and the near-surface plasma is key to characterizing the lunar surface environment and associated potential hazards in which robotic and human explorers will operate. Studies on the Moon will include an investigation of interactions between charged particles and lunar dust.

Future investigations will not only advance our characterization of the basic plasma interactions, which is key to an increased understanding of the organization and evolution of large-scale magnetodynamic systems but will inform key aspects of future plans for planetary exploration.

With its lack of an absorbing atmosphere, the Moon provides a natural observation platform from which to observe the sky, the Sun, geospace, and the Earth. Furthermore, the Moon is locked into synchronous rotation with respect to the Earth and, therefore, always displays the same side to Earth. The opportunities to exploit the Moon as a unique observation platform include:

- **Imaging the heliospheric boundary:** The heliospheric boundaries can be imaged in extreme ultraviolet (EUV) and energetic neutral atoms (ENAs) from either the lunar surface or from a satellite in lunar orbit. Due to the sheer size of our heliosphere and the difficulty in observing its boundaries, little is known about how it interacts with the local interstellar medium. Basic knowledge about the heliospheric boundaries is required to compare our heliosphere with astrospheres of other stellar systems. Such comparisons provide critical information on the current evolutionary stage of stellar winds and stellar mass loss rates, give insight into the stars' local interstellar environments, and possibly enable the assessment of the habitability of other solar systems.
- **Low-frequency radio astronomy observations of the Sun:** Radio emissions from solar coronal mass ejections (CMEs) and solar flares below 10 MHz can be imaged from the lunar surface to probe space from a few solar radii out to 1 astronomical unit (AU). Observations of radio emissions from the Sun allow improved space weather forecasting, improve our understanding of shock formation and evolution in the solar wind, and enable detailed time-dependent mapping of the interplanetary electron density and magnetic field topology (Figure 6.1-2).
- **Imaging geospace:** The iconic image of Earth's ionosphere and the Appleton anomaly (the fingers reaching to the Earth's night side) first made by Carruther's UV camera that was emplaced by the Apollo 16 astronauts on the lunar surface demonstrates the feasibility of

performing this from the lunar surface (Figure 6.1-1). Such imaging can address several compelling science questions related to large-scale coupling mechanisms between various complex regions in geospace from the ionosphere and extending into the magnetosphere. Global observations of ionospheric and magnetospheric phenomena provide measurements that are key to understanding the hazards and impact of space weather in the regions of space where most space agency, commercial, and military space operations occur. These measurements also provide constraints to global ionospheric and magnetospheric models and provide keys to solving compelling science questions associated with the coupling between the solar wind, the magnetosphere, and the ionosphere, and coupling of the high and mid-equatorial regions of the ionosphere [Meier, 1991; Su et al., 2001].

- **Analyzing the composition of the solar wind:** The solar wind reflects the composition of the Sun and physical processes in the corona. Analysis will help differentiate between several theories of solar system formation and physical processes in the solar corona. Ions will be collected on various materials and analyzed on return to Earth. Similar experiments were first done using foils on Apollo missions. Then, the Genesis mission added to the database, although with some complications due to the hard return of the spacecraft to Earth. Additional data gathered in this very simple and inexpensive experiment during upcoming lunar missions will expand the restricted scientific return of Genesis. Specifically, additional elements and isotopes will be accessible, providing missing information on solar formation and evolution.
- **Using the Moon as a base for a high-energy optical solar observatory:** The Sun can be observed with optical and UV telescopes and coronagraphs, vector magnetographs, and X-ray and gamma-ray imaging spectroscopes from the Moon. The benefits of the proposed lunar instrumentation are twofold: (1) enable fundamental advances in scientific understanding of the processes that lead to energy release and the acceleration of energetic charged particles by the Sun and, thus, in other, more distant and more energetic astrophysical objects; and (2) allow further understanding of the conditions that lead to hazardous eruptive solar events, thus providing operationally useful warnings (or “all clears”) to enhance the safety and productivity of crewed missions to the Moon and Mars.

6.4.3 Exoplanet Magnetosphere

There have been several efforts to find exoplanets with magnetospheres. When considering our own solar system, magnetospheres are very common. Of our eight planets, uncertainty exists for only Venus as to whether it was able to generate a magnetosphere. There are several electromagnetic (EM) waves that are generated in and can escape from a planet’s magnetospheres. The lowest frequency EM wave is the left-hand polarized non-thermal continuum (NTC) radiation associated with the interface of hot and cold plasma. It is typically generated in the frequency range of ~10 to 800 kilohertz (kHz) [Green and Boardsen, 2006].

Another radio frequency (RF) emission is generated by the cyclotron maser instability (CMI) mechanism, which derives its named based on the frequency range of the observed emission. It is well known that this type of emission is closely related to the local gyrofrequency being generated above a planet’s aurora from downward streaming electrons and therefore provides important clues as to the presence of a planet’s magnetic field and its strength. For example, the Earth’s intense auroral-related radio emission is called AKR, and the Jovian decametric (DAM) emissions are CMI-related emissions from Jupiter’s auroral zone. The CMI emissions are right-hand polarized, being generated over a broad frequency range (i.e., ~25 to 800 kHz for AKR and ~10 to 40 MHz for DAM).

The third and final radio emission escaping from certain planetary magnetospheres emanates from a planet's radiation belts by the synchrotron mechanism generated by trapped relativistic electrons. The fundamental characteristic of this emission is the narrow beaming pattern generated from the gyrating electrons, which provides the basis for constraints on both the magnetic field and the distribution of charged particles in the inner magnetosphere [Bolton et al., 2001]. Jupiter's decimetric (DIM) radiation ranges from 0.1 to 15 gigahertz (GHz).

It is believed that the intense auroral related radio emission is the best indicator of planetary magnetospheres [e.g., Bastian et al., 2000; Zarka et al., 2001]. The CMI-generated radio emissions produce intense radiation perpendicular to the local magnetic field, but the resulting emission cone can be filled in by refraction or hollow, as shown in Figure 6.4.3-1. For instance, the emission cone of AKR has been observed to be relatively well filled in [Green and Gallagher, 1985] at higher frequencies and may be hollow at the lower frequencies [Calvert, 1987], while the Jovian DAM emissions produce hollow emission cones [Green, 1984], as illustrated in Figures 6.4.3-1a and 6.4.3-1b, respectively. The Earth's AKR emission cone points tailward with partially overlapping northern and southern hemisphere cones (only the northern hemisphere cone at one frequency is shown in Figure 6.4.3-1a) and is not dependent on Earth's rotation or the location of the Moon.

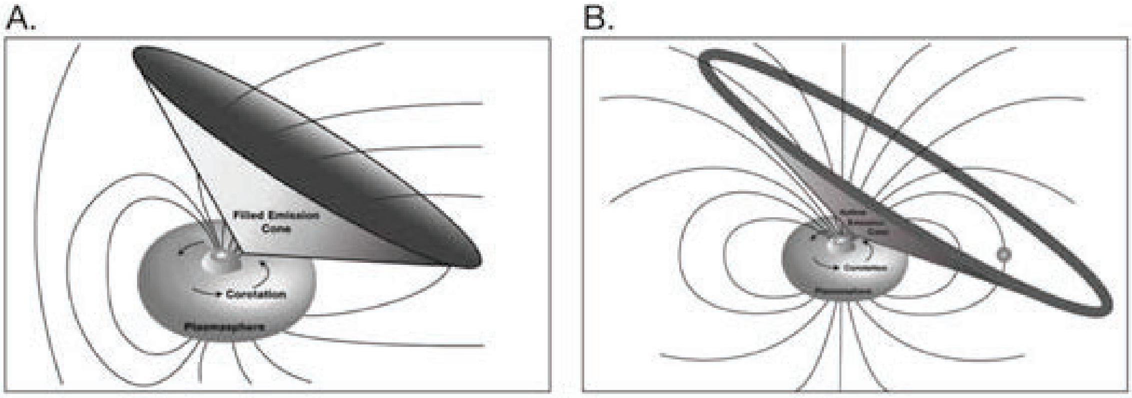


Figure 6.4.3-1. Schematic of Emission Cones of Auroral Radio Emissions

One aspect of the Jovian DAM emission is that it is strongly coupled with the moon Io, which has a thin atmosphere, allowing an ionospheric current to connect field lines from Jupiter and create a constant current and, therefore, a constant aurora and resulting CMI-related radio emissions. These Io-controlled DAM emissions produce hollow emission cones that move with Io around the planet, which has an orbital period of about 42 hours. Io is in an elliptical orbit and is so close to the planet Jupiter that the energy from the strong tidal forces is dissipated through volcanic activity that is so strong on Io that a torus of escaping material is left in its wake that stretches around Jupiter. Alfven waves are set up in the Io torus that produce magnetospheric currents stretching all the way to the Jovian auroral regions and trigger additional CMI emissions that produce a set of nested hollow emission cones.

Near equatorial spacecraft (e.g., the Voyager 1 and 2 missions) observed the Io DAM emissions as a series of arc-like structures in frequency-time spectrograms. The shape of the nested emission cones, in frequency-time spectrograms, are strongly controlled by the higher moments of the Jovian magnetic fields since the strongly right-hand polarized DAM radiation propagating from the source over these intense magnetic islands [Green et al., 2020] suffers significant refraction. In addition, Jupiter's moon Ganymede also produces aurora, not only in the upper atmosphere of Jupiter but also in the very tenuous Ganymede atmosphere since that moon is the only one in the solar system that has been observed to currently generate its own magnetosphere [e.g., Wang et al., 2018]. The rather small Ganymede magnetosphere is anti-aligned with Jupiter, facilitating the exchange of atmospheric constituents and even producing aurora in Ganymede's very tenuous atmosphere.

In the case of both an exoplanet and an exomoon with magnetospheres, a new situation occurs in which the exomoon would be controlling the location of a potential CMI emission cone and producing either a hollow or filled-in emission pattern. From a distant radio observer, periodicities in an observed CMI emission cone pattern, with the radio emission frequency, not only could point to the existence and strength of an exoplanet's magnetosphere but also to the existence of an exomoon. The extent of the emission cone, ranging from completely hollow to completely filled, provides additional information about the extent of the exoplanet's ionosphere. In this manner, the detection and analysis of CMI-generated radio emissions may provide additional information as to the habitability of the exoplanet. To understand the long-term evolution of exoplanetary atmospheres and their suitability for creating a habitable environment that may host life, we must understand not only the stellar environment of these planets but also whether these planets and their associated moons have magnetospheres.

The low-frequency radio spectrum of the objects in the solar system is shown in Figure 6.4.3-2. It is expected that radio emissions from other solar systems are similar, but these have not been measured. Magnetospheric radio emission is a nonthermal process produced by auroral maser emission. The frequency of this emission is directly proportional to the magnetic field strength. Only Jupiter has a B-field large enough to produce radio emission that can be seen from Earth above the ionospheric cutoff. As Figure 6.4.3-2 shows, every other planetary B-field in the solar system emits at much lower frequencies and cannot be seen from Earth. Earth itself produces high flux density auroral kilometric radiation, but it is below 1 MHz and was first detected from space. There have been extensive searches for exoplanet radio emission using ground-based telescopes, but all have come up empty handed. A low frequency radio observatory on the far side of the Moon, as discussed in the next section of this report, can be designed to detect radio emissions not only from solar system objects but also radio emissions from potentially habitable exoplanets.

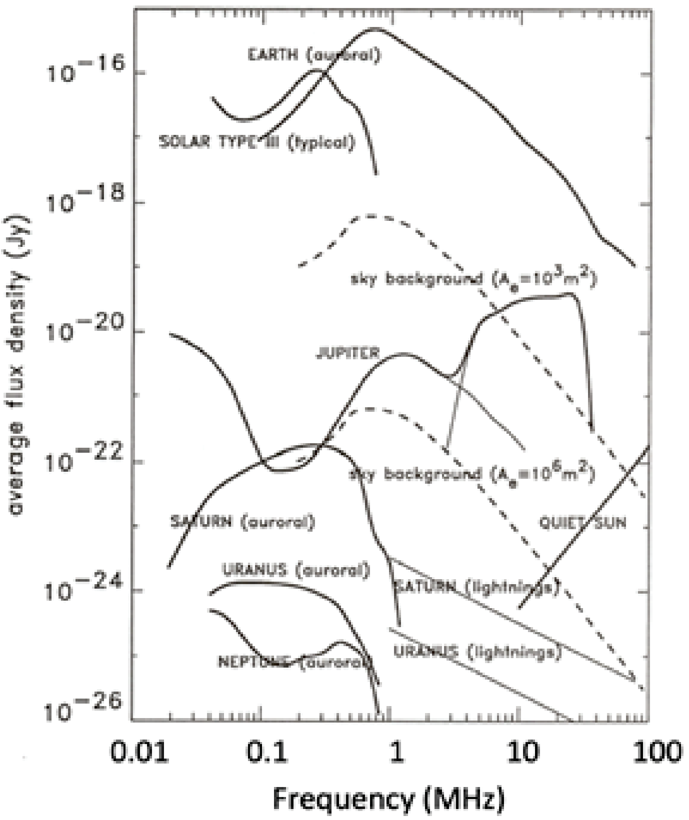


Figure 6.4.3-2. Contributions to Low-frequency Radio Spectrum of the Solar System from the Earth, Sun, and Planets [Zarka, 2007]

6.4.4 IR-Optical-UV Observatories

AstronetX and other organizations are studying sustainable lunar observatory concepts spanning UV, visible, and infrared (IR) wavelengths. For example, there are a number of astrophysical and geophysical phenomena that can be studied using timestamped, broad bandpass imaging and photometric data from modest wide-field imagers attached to lunar landers. Scientific programs include tracking stellar activity and astroseismology, monitoring light curves of transiting exoplanets and interacting variable stars, and mapping properties of the lunar exosphere. Like images from terrestrial observatories, such data from the lunar surface could aid in cislunar space traffic management to ensure safety of flight for robotic and crewed missions. The ecliptic and sky regions at low Sun angles can also be accessed from different landing sites for studying Solar System objects, including for planetary defense purposes.

Key scientific enablers for precision time-domain photometric measurements and diffraction-limited performance of SmallSat-class optical systems (compared with low Earth orbit (LEO) satellites) are the stable platform of the lunar surface and long, uninterrupted visibility periods. These characteristics could enable a future UV-visible, lunar surface-based sparse aperture interferometer capable of extremely high-resolution imaging, deployed robotically or with astronaut assistance over a baseline of at least several hundred meters. Such a facility could resolve the surfaces of stars, monitor photospheric activity of exoplanet host stars that could affect habitability, measure parallaxes to large distances in the galaxy and beyond, probe the inner accretion and debris disks around nascent stars and black holes, and demonstrate technologies and techniques for a future free-flying configuration of telescopes capable of resolving weather patterns and surface features on the nearest exoplanets.

6.5 Lunar Radio Telescope Case Studies

For the purposes of this assessment, three NASA-funded studies to place a radio telescope on the lunar far side were used for the case studies. The original ground rule for these studies was that they must be fully robotic and self-contained missions with no external dependences. The workshop focused on the technical and cost benefits to leveraging the Artemis Program to implement these concepts. *Note that the choice of these case studies should in no respect be seen as an endorsement of these concepts over other possibilities: that is for future decadal surveys to consider.*

A long-wavelength radio telescope on the far side of the Moon has significant advantages compared with Earth-based and Earth-orbiting telescopes, including:

- Enabling observations of the early Universe at wavelengths longer than 10 m (i.e., frequencies below 30 MHz), at which critical cosmological signatures from the Dark Ages are predicted to appear. These wavelengths cannot be observed from the Earth's surface or Earth orbit due to ionospheric absorption and reflection.
- The Moon acts as a physical shield, isolating a lunar surface telescope from radio interference or noise sources from the Earth's surface, the ionosphere, Earth-orbiting satellites, and the Sun's radio emission during the lunar night.

6.5.1 FARSIDE

NASA Astrophysics funded the first engineering design study of an interferometric array for possible deployment by a large CLPS lander on the lunar far side [Burns et al. 2019a, 2021]. FARSIDE is one of the astrophysics Probe-class missions considered by the Astro2020 decadal survey.

The FARSIDE architecture and operations concept were developed via a series of studies at the Jet Propulsion Laboratory (JPL) [Burns et al. 2019a, 2021]. These studies assessed the technical feasibility of the instrument and the mission, and the cost-realism for a Probe-class mission. The current FARSIDE design architecture consists of 128 non-cospatial orthogonal pairs of antenna/receiver nodes distributed over a 10-kilometer (km) diameter in a four-arm spiral configuration, as shown in Figure 6.5.1-1. The nodes are deployed in a zigzag pattern, with the first antenna of the pair having a vertical polarization axis (Ey) and the next having a horizonal axis (Ex), producing measurements of all four Stokes parameters. The FARSIDE payload mass is estimated to be 1750 kilograms (kg), which would be delivered to the lunar surface by a large commercial lander. Four single-axle teleoperated rovers would deploy the nodes, which are connected to the base station (lander) by science tethers, providing communications, data relay, and power.

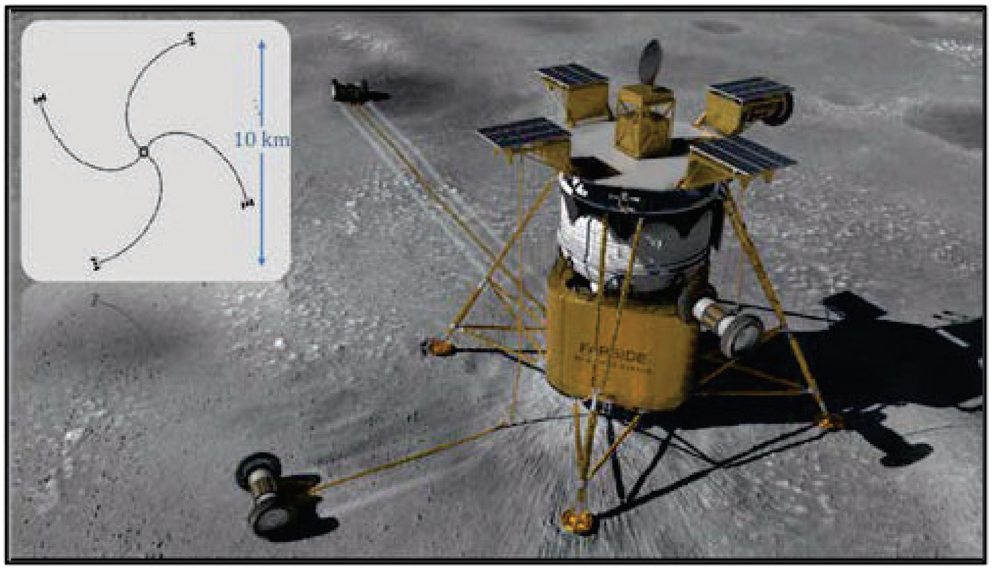


Figure 6.5.1-1. Three Components of FARSIDE: Commercial Lander carrying Base Station, Four Single-axle Rovers to Deploy Antenna Nodes, and 128×2 (two orthogonal polarizations) Node Antenna Array
The array will be deployed in a spiral pattern to produce good u-v coverage. Tethers connect the base station to the nodes, providing communications and power. A lunar-orbiting communication satellite will relay data to Earth. [Image courtesy of Blue Origin]

Beginning with the distinctive radio-quiet characteristics of the far side as a requirement, an astronomical array at frequencies of 0.1 to 40 MHz is driven by sensitivity and spatial resolution. The sensitivity is determined by the number and type of antennas used in the array, and the resolution is governed by the maximum baseline. For FARSIDE, 100-meter (m) tip-to-tip thin-wire antennas are used. It was determined that 128×2 dipole antennas provide the needed sensitivity to span the science cases described in Burns et al. [2019a], especially probing the Dark Ages global signal, the space plasma weather, and magnetospheres in exoplanetary systems. With an array diameter of 10 kilometers (km), FARSIDE achieves a resolution of 10° full width at half maximum (FWHM) at 200 kHz and 10 arcminutes (arcmin) at 15 MHz.

Sensitivity specifications for FARSIDE are summarized in Table 6.5.1-1. The array sensitivity (i.e., minimum detectable flux density) in Table 6.5.1-1 depends on the frequency bandwidth, the integration time, the system temperature, and the effective area of the array. The effective area is determined by the dipole length and the antenna impedance. This was modeled using NEC4.2 simulations that consider that the dipole wires rest directly on the regolith. The system temperature depends on the sky and regolith temperatures and the front-end amplifier. See Burns et al. [2019a] for complete details of the modeling and simulations.

Table 6.5.1-1. FARSIDE Sensitivity

Quantity	Value
Frequency coverage	0.1 – 40 MHz (1400 × 28.5 kHz channels)
Antenna efficiency	6.8×10^{-6} @ 200 kHz; 9.5×10^{-5} @ 15 MHz
System temperature (T_{sys})	1×10^{6} K @ 200 kHz; 2.7×10^{4} K @ 15 MHz
Effective collecting area (A_{eff})	~12.6 km^2 @ 200 kHz; 2240 m^2 @ 15 MHz
System equivalent flux density ($2k_BT_{sys}/A_{eff}$)	230 Jy @ 200 kHz; 2.8×10^{4} Jy @ 15 MHz
1σ Sensitivity for 60 sec, $\Delta\nu=\nu/2$	66 mJy @ 200 kHz; 933 mJy @ 15 MHz

The FARSIDE instrument front end uses the electrically short antennas to achieve sky background noise-limited observations. On the lunar far side, the lunar highlands are thick, have low conductivity, and vary slowly with depth, thus removing the need for a ground plane. The net impact of this multipath effect is to introduce a direction-dependent component to the array synthesized beam. FARSIDE will use an orbital beacon for calibration and to map both the antenna beam pattern and the array synthesized beam to capture this effect. The 100-m antennas are embedded within the tether and will be placed directly on the lunar surface. The array leverages existing designs from high-heritage front-end amplifiers, fiber optics, and the correlator system based on ground-based observatories such as the Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) [Anderson et al., 2018].

The concept design calls for operations during the lunar night as well as the lunar day, using proven low-temperature electronics and batteries. Recent tests indicate that core constituents (e.g., resistors and capacitors), forming the basis of the electronic components of the FARSIDE receiver nodes, are capable and survivable to temperatures less than –180 degrees Celsius (°C) [Ashtijou et al., 2020].

The 128 antenna node pairs are distributed along four spirals, as shown in the Figure 6.5.1-1 insert. This configuration with four JPL Axel rovers would allow the full deployment of the array in one lunar day. A tether connects the nodes to one another and to the central base station for data transmission and power. For each spiral arm, the rover would carry a set of antenna nodes from the base station, unspooling the tether, before returning to the base along a different path. The landing site and rover path are assumed to be relatively flat and free of obstacles with scale sizes $\gtrsim$1 m.

The base station includes solar panels and batteries to provide power for the receivers and the signal processing using an FX correlator [Kocz et al., 2014], as well as data relay to Earth via a communications satellite. The rovers draw power along the tether from the base station. The rover will either be operated from Earth (with ≈5-second (sec) latency) or teleoperated via astronauts aboard the lunar Gateway (with ≈0.5-sec latency) [Burns et al. 2019b]. After cross-correlation via the FX correlator, visibility data will be conveyed to Earth for further analysis. This is estimated to be about 130 gigabytes (GB) of data per 24-hour period. The goal is to process 10,000 square degrees of the sky every 60 sec over 1400 frequency channels. This would then produce dynamic spectra at the location of each bursting object, including Type II/III solar emissions and bursts in any of the several thousand nearby exoplanetary system counterparts, as well as CME-driven auroral emissions from nearby terrestrial exoplanets. The array is planned for operations over 5 years. At its lowest frequency, FARSIDE would operate two orders of magnitude below the Earth's ionospheric cutoff.

6.5.2 Lunar Crater Radio Telescope (LCRT)

The proposed design of a Lunar Crater Radio Telescope (LCRT) on the far side of the Moon (Figure 6.5.2-1) uses a projectile-based anchoring system to deploy tethers and wire mesh in a 1- to 2-km diameter lunar crater with suitable depth. This deployment will create a 350-m diameter parabolic reflector and a 35-m feed inside the crater. LCRT will be one of the largest filled-aperture radio telescopes in the Solar System, similar to the former Arecibo telescope (305-m diameter) and the Five-hundred-meter Aperture Spherical Radio Telescope (FAST) (500-m diameter) on Earth.

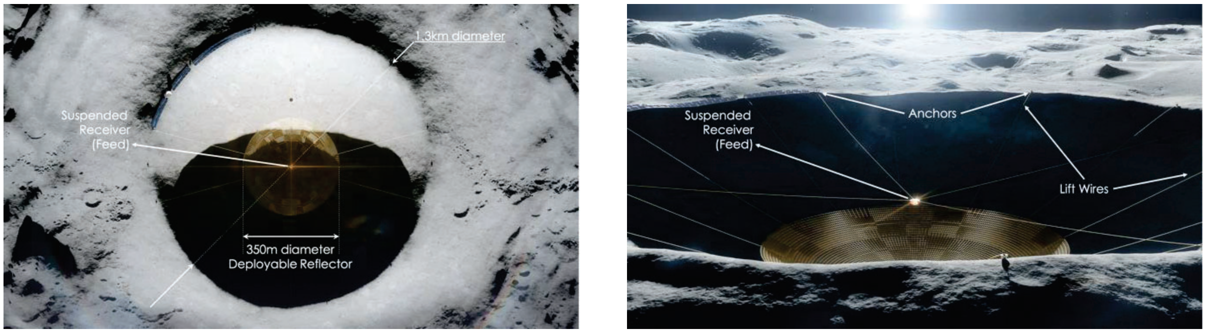
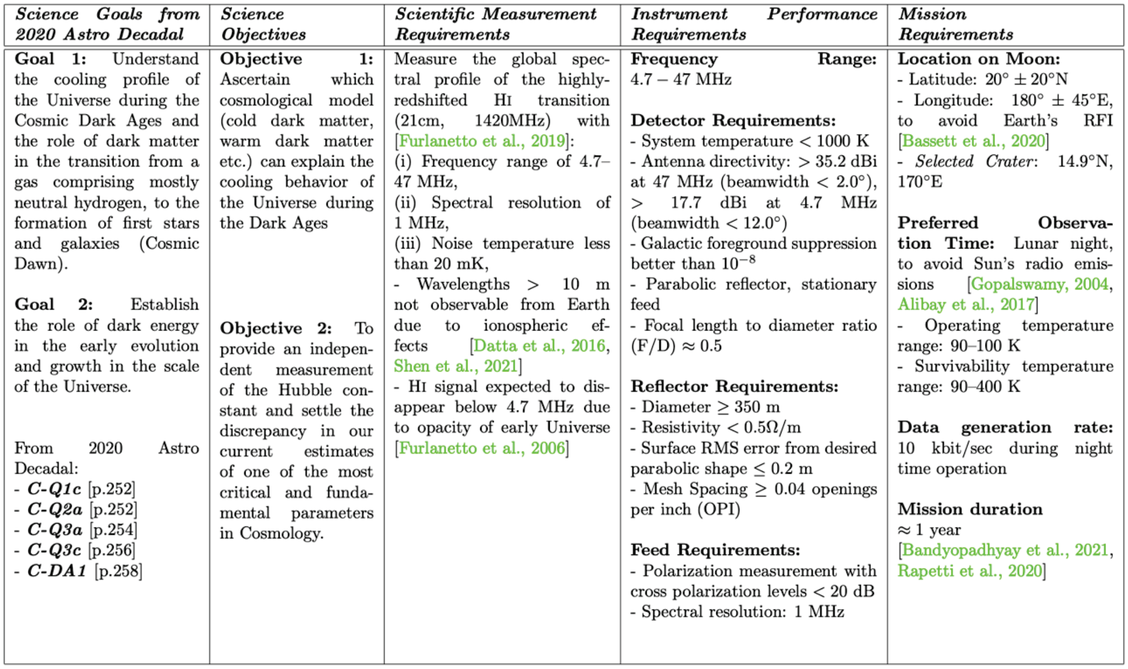


Figure 6.5.2-1. Concept Art of LCRT on far Side of Moon

LCRT will enable scientific discoveries in the field of cosmology by observing the early universe in the 6- to 64-m wavelength band (i.e., 4.7- to 47-MHz frequency band), which has not been explored for cosmological observations to date. The LCRT's Science Traceability Matrix (STM) is shown in Figure 6.5.2-2.



Science Goals from 2020 Astro Decadal	*Science Objectives*	*Scientific Measurement Requirements*	*Instrument Performance Requirements*	*Mission Requirements*
Goal 1: Understand the cooling profile of the Universe during the Cosmic Dark Ages and the role of dark matter in the transition from a gas comprising mostly neutral hydrogen, to the formation of first stars and galaxies (Cosmic Dawn). **Goal 2:** Establish the role of dark energy in the early evolution and growth in the scale of the Universe. From 2020 Astro Decadal: - ***C-Q1c*** [p.252] - ***C-Q2a*** [p.252] - ***C-Q3a*** [p.254] - ***C-Q3c*** [p.256] - ***C-DA1*** [p.258]	**Objective 1:** Ascertain which cosmological model (cold dark matter, warm dark matter etc.) can explain the cooling behavior of the Universe during the Dark Ages **Objective 2:** To provide an independent measurement of the Hubble constant and settle the discrepancy in our current estimates of one of the most critical and fundamental parameters in Cosmology.	Measure the global spectral profile of the highly-redshifted HI transition (21cm, 1420MHz) with [Furlanetto et al., 2019]: (i) Frequency range of 4.7–47 MHz, (ii) Spectral resolution of 1 MHz, (iii) Noise temperature less than 20 mK, - Wavelengths > 10 m not observable from Earth due to ionospheric effects [Datta et al., 2016, Shen et al., 2021] - HI signal expected to disappear below 4.7 MHz due to opacity of early Universe [Furlanetto et al., 2006]	**Frequency Range:** 4.7 – 47 MHz **Detector Requirements:** - System temperature < 1000 K - Antenna directivity: > 35.2 dBi at 47 MHz (beamwidth < 2.0°), > 17.7 dBi at 4.7 MHz (beamwidth < 12.0°) - Galactic foreground suppression better than 10^{-8} - Parabolic reflector, stationary feed - Focal length to diameter ratio (F/D) ≈ 0.5 **Reflector Requirements:** - Diameter ≥ 350 m - Resistivity < 0.5Ω/m - Surface RMS error from desired parabolic shape ≤ 0.2 m - Mesh Spacing ≥ 0.04 openings per inch (OPI) **Feed Requirements:** - Polarization measurement with cross polarization levels < 20 dB - Spectral resolution: 1 MHz	**Location on Moon:** - Latitude: 20° ± 20°N - Longitude: 180° ± 45°E, to avoid Earth's RFI [Bassett et al., 2020] - *Selected Crater*: 14.9°N, 170°E **Preferred Observation Time:** Lunar night, to avoid Sun's radio emissions [Gopalswamy, 2004, Alibay et al., 2017] - Operating temperature range: 90–100 K - Survivability temperature range: 90–400 K **Data generation rate:** 10 kbit/sec during night time operation **Mission duration** ≈ 1 year [Bandyopadhyay et al., 2021, Rapetti et al., 2020]

Figure 6.5.2-2. LCRT STM

The ConOps for constructing the LCRT is shown in Figure 6.5.2-3; key phases are as follows:

Step 1. A spacecraft approaches the selected crater on the far side of the Moon and lands on the crater floor.

Step 2. The spacecraft fires anchors, with lift wires, to the crater rim using a pyro/compressed-gas-based projectile mechanism.

Step 3. The spacecraft tensions these lift wires, which causes the anchors to grip into the lunar regolith and provide sufficient tension for the deployment process.

Step 4. Subsequently, the 35-m Log Periodic Antenna feed is hoisted and deployed using a pulley system.

Step 5. Next, the 350-m diameter parabolic reflector is deployed along an origami fold pattern, using the pulley system.

Step 6. Finally, the deployed LCRT is calibrated using a known source from a beacon CubeSat.

Further details of the ConOps, robotics operations, the design of LCRT's feed and reflector, and mass, power, cost, and risk budgets are discussed in Bandyopadhyay et al. [2021a, 2021b], Gupta et. al. [2022], Wang et. al. [2023], and Arya et. al. [2023].

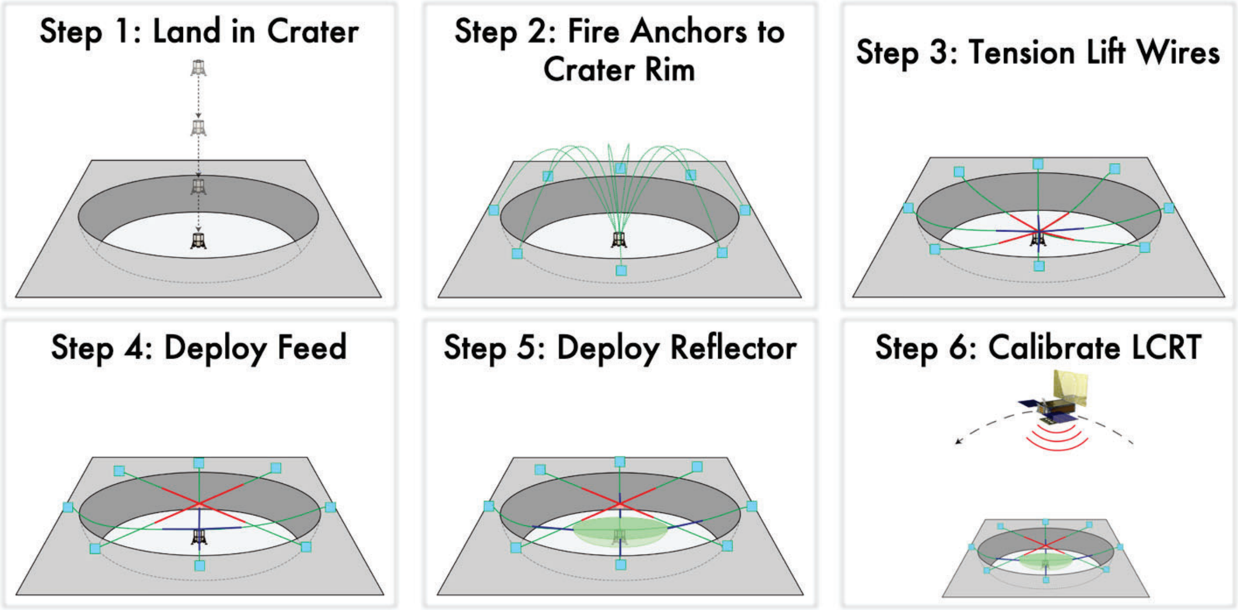


Figure 6.5.2-3. LCRT ConOps

6.5.3 FarView

FarView is a NASA Innovative Advanced Concepts (NIAC) funded study (completed in 2021) for a low-frequency (5 to 40 MHz) radio interferometer consisting of 100,000 dipole antennas, distributed in a subarray architecture across 200 km^2 of the lunar surface. One of the unique aspects of FarView is that it would be built *in-situ* using mostly material extracted from the lunar regolith by Lunar Resources, Inc.'s developed technologies. FarView would be built on the radio-quiet lunar far side to reduce background noise, enabling the primary science goal of studying the cosmic Dark Ages. The Dark Ages and Cosmic Dawn epochs of the Universe can be uniquely probed using the redshifted 21-cm signal. FarView will fill in the missing data during the cosmic Dark Ages and Cosmic Dawn. See Section 6.4.1 of this report for a discussion of this epoch of the Universe.

FarView is designed to address the recommendations of the recent Astro2020 decadal review regarding the cosmic Dark Ages by measuring its three-dimensional power spectrum. The principal product from FarView will be tomographic maps tracing the evolution of the Universe from before the birth of the first stars through Cosmic Dawn. Spatial fluctuations in the Dark Ages signal are governed by linear structure formation, allowing precise predictions of expected signal for standard cosmology. FarView's sensitive interferometric measurements can uniquely test the standard cosmological model at the onset of structure formation. Departure from these well-constrained predictions will provide insights into new physics. FarView will have a broad science portfolio in addition to the cosmology research.

Solar System science will include imaging of solar Type II radio bursts associated with CMEs at >2 solar radii, monitoring at <10 MHz the variable solar wind's impact on the auroral flux density, and atmospheric lightning from outer planets. In the solar neighborhood, FarView will detect Type II/III radio bursts from nearby stars with exoplanets out to ~10 parsec (pc) and detect terrestrial planet magnetospheres in nearby exoplanets, produced by coherent radio emission at <1 MHz. Because FarView will image the entire sky hemisphere above the lunar horizon every few minutes, it will greatly expand our knowledge of radio variable/transient sources, including fast radio burst sources, flares in stars, neutron stars, and black holes, and will likely discover new types of radio variables. Finally, very local to FarView, it will be able to sound the mega-regolith on the Moon and its transition to bedrock expected at ~2 km below the surface. Once fully populated with its 100,000 dipole antennas, FarView will be the most sensitive low-frequency radio telescope ever built.

To achieve this high sensitivity, FarView must be built in the most radio-quiet locations on the lunar far side. The far side southern hemisphere between 20° S and 60° S latitude and 120° and 220° E longitude was found to be particularly rich in sites that likely meet all science and manufacturing requirements. A smaller number of additional sites can be found in the northern hemisphere of the lunar far side. FarView will be built using a subarray architecture: ~200 subarrays, each containing ~500 10-m dipole antennas, distributed across ~200 km^2 in a core-halo arrangement. Figure 6.5.3-1 illustrates an example of FarView subarrays in the Pauli impact basin. The core-halo architecture has a compact core (the dashed line in Figure 6.5.3-1) with approximately uniform spacings of subarrays out to a diameter of ~6 km and an outer quasi-power-law distribution of subarrays out to ~14 km. FarView subarrays will have an average of 500 dipole antennas, but the number of dipoles in a subarray is somewhat arbitrary. The 500-dipole number approximates what one manufacturing rover can build in 1 lunar workday (12 Earth days), and the total area occupied by a single subarray is ~0.18 km^2. The right side of Figure 6.5.3-1 provides greater detail on the subarrays. Each FarView subarray will have its own *in-situ* built power infrastructure (i.e., ~1 kilowatt (kW) solar arrays, batteries, and all power lines). Each dipole will have an average separation of ~17 m from adjacent dipoles within and between rows.

FarView is enabled and made affordable by two Lunar Resources-developed technologies that first extract metals from regolith, purify the metals, and use them to manufacture the dipole antennas, solar arrays, and power lines. The Molten Regolith Electrolysis (MRE) system (Figure 6.5.3-2) reduces the regolith oxides into aluminum, iron, silicon, magnesium, and oxygen, and needs only electrical energy (no reagents or beneficiation of regolith). Lunar

Resources is demonstrating MRE technology under NASA and National Science Foundation (NSF) support, raising its technology readiness level (TRL) from 3 to 5. Once the metals are extracted, a vacuum vapor deposition system (previously flown in space and at TRL 8), integrated with a lunar rover and benefiting from the high vacuum environment on the Moon, will directly deposit thick metallic film dipole antennas, interconnections, power lines, and solar cells to build the observatory components.

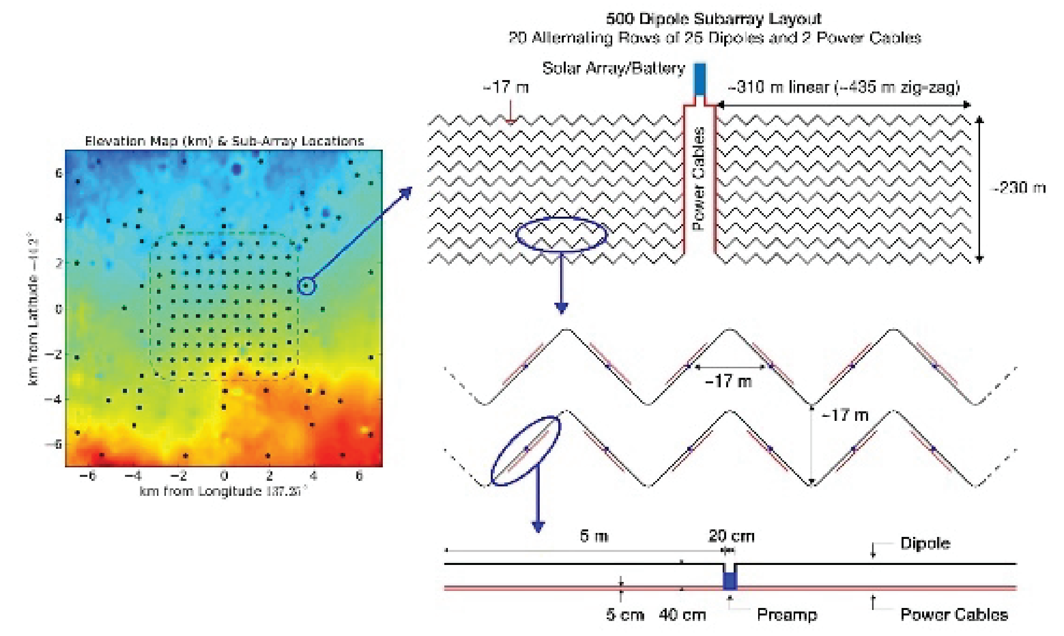


Figure 6.5.3-1. FarView Antenna Notional Distribution
(Left: full interferometer array in the crater Pauli, black dots represent subarrays. The core-halo architecture can be seen in the uniformly distributed core (inside the dashed line), and the quasi-power law distribution of dipoles outside the core. Upper right: notional example of a FarView subarray. Middle right: dipole row detail, indicating dipole spacing and orientation. Bottom right: individual dipole details.)

Figure 6.5.3-2. Schematic of FarView Molten Regolith Electrolysis System

To build FarView, a total of ~1 to 2 metric tons of hardware must be landed. This can be achieved with a single landing of all the hardware or multiple landings delivering subsets of hardware. All FarView extraction and manufacturing systems are highly autonomous and do not need regular human tending. These systems operate principally during lunar daytime and have minimal communications needs, a data link of ~1 megabits per second (Mbps), for ~30 min approximately every 6 hours during lunar daytime. After startup, the system will be in a fully autonomous mode with the MRE system producing and packaging metals, and the rover(s) fabricating thick film dipole antennae and thin film solar cells directly on the lunar surface and integrating them with fabricated power lines. During lunar night, all manufacturing processes are in hiatus, the rovers are parked, and the dipole antennas are gathering science data. Command and control communications are expected to be reduced relative to daytime operations. Science data flow, both from the individual dipoles to the central processing hub and from the hub back to Earth, is substantial. The current estimate is a rate of ~5 terabytes (TB) per 24-hour period for partially processed data that needs to be sent to Earth. Efforts are underway to develop techniques to reduce this rate. Regardless, an optical communications system will be required for FarView science data to meet the data volume requirements.

Since FarView builds its own power network, power systems do not need carried from Earth to power the array. The MRE system can be powered by *in-situ* built power systems, but landing a 40- kW power system to supply power for 6 months with the initial landing of hardware would greatly benefit the initial setup, shortening the time for the system to come online and reducing mission risk. The MRE system and its thermal environment are also used as a “thermal wadi” area, where rovers can be parked to reduce the impact of the lunar night.

Astronaut support is not required to build FarView, but astronaut support during the initial landing to aid in the initial setup and occasional (~every few years) astronaut visits to replace/repair/upgrade aspects of the rovers and other hardware would be useful to keep the observatory in good working condition.

FarView will take 3 to 5 years to build, depending on the amount of hardware landed, the realized extraction and manufacturing rates, and the performance characteristics of the rovers. The *in-situ* manufacturing allows for the key observatory components to be repaired or replaced as needed. FarView will have a lifetime of multiple decades.

6.5.4 Site Selection

The Moon can be modeled as a straight edge such that the diffraction of radio waves around the edge can be calculated analytically. The electrical properties of the lunar material must be included, as well as the presence of lunar material beyond the edge where the diffraction occurs. Takahashi [2003] used a finite difference time domain (FDTD) algorithm to numerically simulate the electromagnetic environment. Bassett et al. [2020] use advances in software and computing resources to extend Takahashi's method by directly simulating higher frequency waves and including lunar properties (e.g., topography and density profile) using the same underlying simulation framework. The results show that as the frequency of the radiation is increased, the amount of attenuation directly behind the Moon becomes greater and the size of the region defined by a given amount of attenuation widens (Figures 6.5.4-1 and 6.5.4-2). This behavior is to be expected because as the frequency is increased the waves will be diffracted by a smaller amount, which leads to greater attenuation at any given point on the far side. Although performing FDTD simulations at frequencies in the MHz range is difficult due to computational limits, results for frequencies between 5 to 100 kHz can place a lower limit on the level of attenuation. Elevation data from the Lunar Orbiter Laser Altimeter (LOLA) instrument on the Lunar Reconnaissance Orbiter, used to evaluate the effect of the topography of the Moon on the intensity of the RFI, show that while the craters of the Moon do have an effect on the propagation of radio waves, the effect in the intensity of these waves on the far side is small, less than 5 dB at most.

Even at frequencies as low as 100 kHz, RFI signals will be attenuated by at least 80 dB over a large portion of the far side. When the frequency is increased to 10 MHz, the quiet region covers nearly the entire far side, including the South Pole Aitken Basin. This presents opportunities to deploy low-frequency experiments in conjunction with lunar studies at geologically interesting locations on the far side (e.g., the Schrodinger crater) [Kramer et al., 2013].

Other factors that impact site selection include: 1) avoiding the equatorial regions to minimize thermal effects on spacecraft, antennas, and science instruments; 2) high crustal thickness and well-mixed regolith to minimize interactions of the radio antenna beam with subsurface reflectors; 3) low slopes, low rock abundance, and avoidance of geological structures;
4) preference for landing on a flat topographic high point to maximize sky accessibility;
5) smooth horizon with, at a minimum, 360° panoramic, reasonably high-resolution imaging of horizon from the telescope location so the horizon is accurately known. Some potential sites are shown in Figure 6.5.4-2.

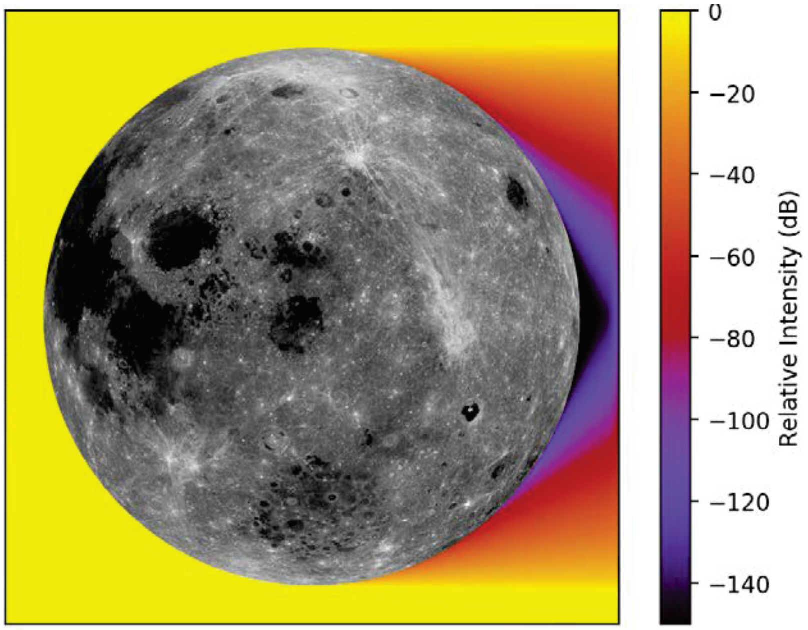


Figure 6.5.4-1. Results of 4000- by 4000-km FDTD Numerical Simulation of Lunar Radio Environment at 30 kHz
RFI incident from the left is attenuated behind the Moon on the right. Higher frequencies exhibit even greater levels of attenuation due to the decreasing effect of refraction around the limb of the Moon [Bassett et al., 2020].

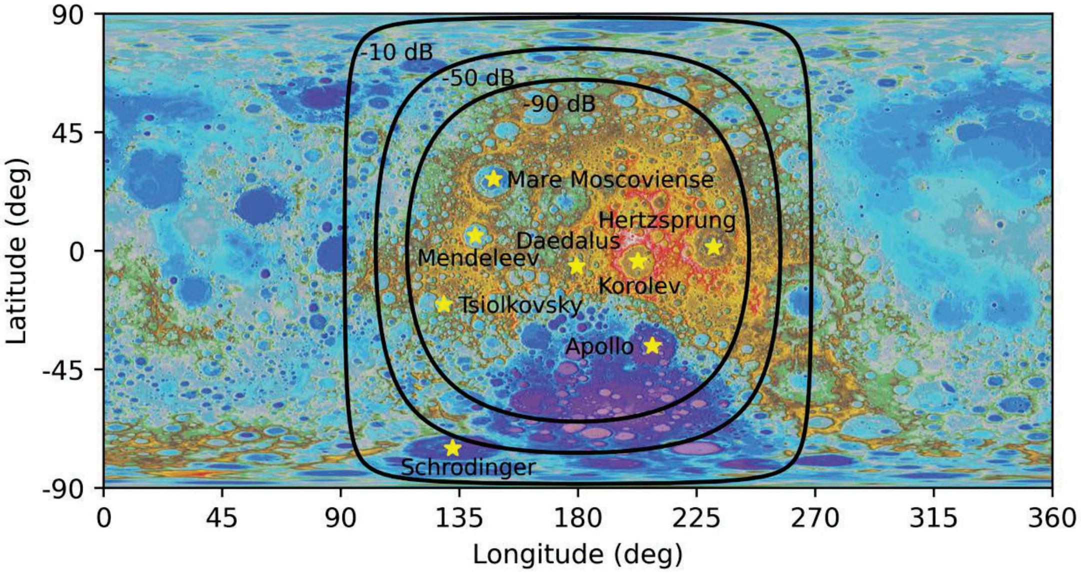


Figure 6.5.4-2. Map of RFI Suppression at 100 kHz based on Numerical Simulations from Bassett et al. [2020]. Contours indicate suppression of –10, –50, and –90 dB relative to incident intensity. Map colors indicate elevation. Yellow stars signify several craters that may be of interest to low-frequency radio experiments and/or lunar studies.

6.5.5 Lunar Surface Electromagnetics Experiment (LuSEE)

The Lunar Surface Electromagnetics Experiment (LuSEE) was selected in June 2019 by NASA in the Lunar Surface Instrument and Technology Payloads (LSITP) for the CLPS Program. LuSEE is split into two payloads on two separate landers:

- **LuSEE "Lite"** to the Schrödinger Basin (south pole far side) on the CP-12 mission. The payload is based on the Parker Solar Probe FIELDS experiment flight spare hardware [Bale et al., 2016]. This will provide measurements of surface plasma physics and waves, DC electrostatic potentials, dust impacts, and coordination with LITMS/LMS (magnetotellurics).
- **LuSEE "Night"** to the far-side mid latitudes on the CS-3 mission in a collaboration with the DOE Brookhaven National Laboratory and Lawrence Berkley Laboratory. The goal is low-frequency radio astronomy (< ~50 MHz) with standalone operations through the lunar night, including radio astrophysics/cosmology pathfinder. The landing site will be on the lunar far-side landing side at mid latitudes with full EMI control.

O-4. Fully robotic missions to deliver scientific payloads to the lunar surface have been studied and are feasible.

7.0 Lunar Environment Challenges and Mitigations

The lunar surface is an extreme environment in which to operate telescopes. These extremes include dust and charging, large thermal excursions, sustaining power through the lunar night, maintaining communications to the far side and extreme lighting conditions. The consideration of augmenting robotic exploration with human exploration involves balancing risk and opportunity. Part of that balance involves understanding and addressing the challenges to both the human and robotic elements that are posed by the environment.

Merging human spaceflight and robotic exploration is challenging on many levels—technical, political, motivational, financial, and opportunistic. There are many tasks humans can do better or more effectively than robots, but humans are demanding on resources and must be kept safe. Humans are only productive 15 to 20% of the time, require a lot of fuel, and are fussy about warmth, atmosphere, and radiation. Robots and surface observatories also have issues—they are sensitive to dust, electrostatic discharge (ESD), and cosmic rays— and may be unable to deal with unexpected situations or technical challenges. Any solution, whether human or robotic, requires power, bandwidth, time, a degree of cleanliness, thermal control, micrometeoroid and orbital debris (MMOD) and radiation protection, logistics, and maintenance capabilities.

The workshop explored some of the engineering challenges faced by any mission and, in particular, those aspects of the human presence.

F-2. While the lunar surface environment is challenging, with dust contamination and maintaining a far-side radio quiet zone being the major concerns, no showstoppers to using the Moon as a platform for science observatories were identified.

7.1 Lunar Dust

With a return to the lunar surface in the Artemis era, there is no doubt that the lunar regolith will pose a challenge. Apollo taught us just how insidious the lunar dust can be. The accounts from astronauts, as well as the documentation of problems caused by dust across several systems, alerted us to the significance of the lunar dust problem [Gaier, 2005]. As we plan for longer stays on the surface, this problem will only amplify. If we are to create a sustainable lunar architecture with a variety of lunar assets, then dust mitigation needs to be at the forefront of mission design.

To understand the challenge of lunar dust, it is important to know the physical and electrical characteristics of the dust. Lunar regolith is angular, abrasive, and irregular in shape. Regolith is the fragmental layer covering the lunar surface, independent of rock size or composition [McKay et al, 1991]. It was created by the bombardment of the solid lunar crust by meteoroids, solar UV flux, solar wind, radiation, etc. over billions of years. During this process, agglutinates were formed by micrometeorite impacts. Agglutinates are fused particles of impact glass, rock, and mineral fragments (<1 mm in size). The term "dust mitigation" is widely used, although the definition of dust itself varies depending on the subject area. The geologic definition typically refers to particles less than 20 microns (µm). For the purpose of dust mitigation, dust is defined to be all lunar particulate that will need to be mitigated. The sizes of interest will vary depending on tolerance of systems. For example, the human systems (i.e., lungs) concerns include the inhalable particles (<10 µm) and the respirable range (<2.5 µm) that can deposit more deeply into the lungs. A rule of thumb for lunar regolith is 50% of the regolith (by weight) is less than 50 µm, and 20% of the regolith is less than 20 µm. Roughly 1% of the regolith is less than 1 µm. The average particle size of lunar dust is 72 µm.[6] Lunar dust has interesting electrostatic and magnetic properties that add to the challenge while providing the opportunity for novel mitigation techniques.

The dust challenge can be approached stepwise as follows: 1) the problems it will cause, 2) the hardware/systems it will impact, 3) the solutions, and 4) testing. It is important to look at the insight learned during Apollo. As Gene Cernan, Apollo 17 Commander, stated, "I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon." Apollo uncovered a plethora of issues [Gaier, 2005], including clogging of joints and mechanisms, human health toxicology, false instrument readings, vision obscuration, abrasion of surfaces, failures of seals, and thermal control. In the Artemis era, dust mitigation should be a consideration for mechanisms, electronics, connectors, seals, softgoods, filtration, crew health and monitoring, thermal systems, power systems, optical systems, and plume surface interactions, among others. When we envision the current lunar architecture and how it will develop as Artemis progresses, almost every aspect of the architecture should have a dust mitigation strategy. Currently, EHP, HLS, Gateway, Orion, and CLPS all have dust mitigation requirements and solutions in work. As the Artemis Program continues and more assets are located on the lunar surface (i.e., habitats, rovers), it will become even more important to understand the dust challenge and how to mitigate against it. Note that the challenges of lunar dust encompass both the natural environment as well as induced environments (i.e., plume surface interactions and crew/vehicle activities.)

In tackling dust mitigation, there are four components to dust management: tolerating dust exposure, detecting/monitoring dust, controlling entry of dust into vehicles or systems, and removal of dust. When we think about solutions for dust mitigation, we should consider architectural solutions, operational solutions, passive technologies, and active technologies [International Agency Working Group, 2016]. Examples of architectural and operational solutions include suit ports, airlocks, mudrooms, porches, landing site selection, prepared landing pads, and optimized EVA and traverse planning. Examples of active technology solutions include electrostatics, compressed air, vacuum, electrodynamic dust shield, and more. Examples

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[6] For reference, a human hair is 100 µm, pollen is 30 µm, most bacteria are 0.3 µm, and smoke is 1 µm.

of passive technologies includes high efficiency particulate air (HEPA) filters, cyclone separators, soft walls, surface coatings, coveralls, dust traps, brushes, tape, wipes, etc. NASA is working with commercial partners through various solicitations opportunities to advance dust mitigation technology solutions.

Every designer of a piece of hardware going to the lunar surface should think about a dust mitigation strategy from the very beginning. At a high level, a dust mitigation strategy includes six steps: understand the natural environment, understand the induced environment, understand the hardware or system's tolerance to dust, write dust requirements, select dust mitigation solutions, and test hardware in dusty environments.

More information on understanding the natural environment can be found in the Design Specification for Natural Environments (DSNE) [SLS-SPEC-159, 2021]. Understanding the induced environment is dependent on the mission, spacecraft, and ConOps. For testing in dusty environments, more information can be found in NASA-STD-1008, Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments [NASA-STD-1008, 2021]. This NASA Technical Standard establishes minimum requirements and provides guidance for testing systems and hardware to be exposed to dust in planetary environments. It provides tables with expected lunar sources of dust for four different environments: planetary external, planetary pressurized, in-space pressurized, and in-space external. It provides information on simulant preparation and storage, as well as simulant loading definitions. It goes into detail about nine different types of testing practices for hardware that will be exposed to dusty environments. This includes aerosol ingestion testing, abrasion testing, optical testing, thermal testing, mechanisms testing, seals and mating surfaces testing, reactivity testing, electrostatics properties, and plume surface interaction testing. NASA-STD-1008 also contains information on simulants and facilities for testing. In addition to NASA-STD-1008, a Dust Mitigation Best Practices Guide will be available in early fiscal year (FY) 2023 [NASA Dust Mitigation Best Practices Guide, to be published].

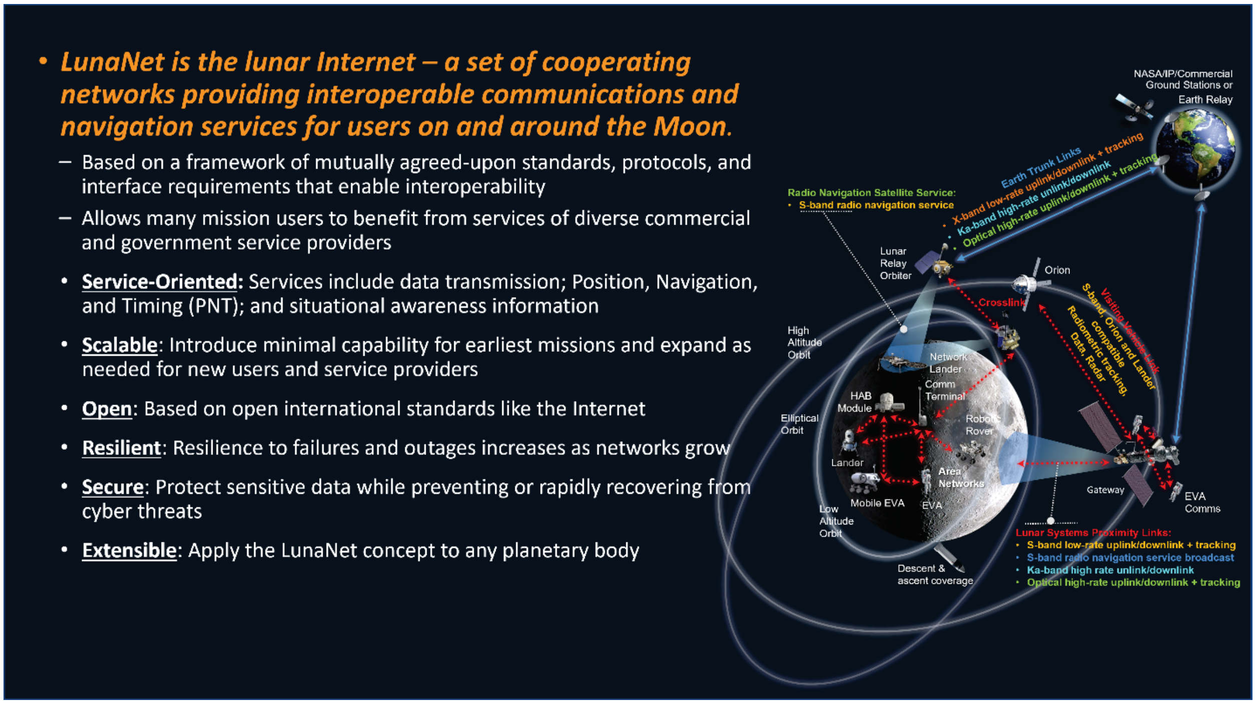
There are several different areas of consideration within lunar dust mitigation, each with its own challenges and potential solutions. Some of these areas include mobility, thermal, reactivity, electrostatics, aerosols, sensors and instrumentation, adhesion, abrasion, optical, simulants, surfaces/coatings/surface modifications, plume surface interactions, toxicity and health concerns, and dust deposition, among others. For example, consideration of electrostatics is important both for operations on the surface and testing on the ground. In general, the movement and deposition of granular materials is dependent on their electrostatic properties, which can dominate all other forces in high-vacuum and low-gravity environments. Electrostatics testing is important for any hardware that could have its properties or operation altered by the electrical properties of dust. This includes electrostatic properties of granular materials, ESD circuit shorts from accumulated dust, and electrical arcing [Buhler et al., 2007].

As we expand our presence on the lunar surface, lunar dust will be inevitable. It will be a feature of all lunar surface science investigations, whether welcome or not. Mitigating dust is critical for the success of lunar surface science and exploration investigations, whether human-led or robotic. It will be necessary to ground test future instruments against the effects of lunar dust [NASA-STD-1008, 2021]. For example, rovers that may carry scientific payloads need to provide mobility as the wheels traverse through the regolith. Investigations that involve mechanisms (e.g., drill or arms transporting samples to instruments) need to understand how to mitigate dust to improve reliability and extend operations. Imagery, optics, or solar panels need to protect their surfaces from the abrasiveness of lunar dust. Incorporating certain solutions into the design of future investigations may be necessary.

7.2 Communication and Navigation

The approach to lunar Communications, Pointing, Navigation, and Timing (CPNT) used for Apollo relied on the Deep Space Network (DSN) and its three ground stations spaced roughly 120° around the world to provide nearly continuous coverage. A terrestrial ground network, however, cannot provide service to the polar regions or the far side. The Apollo Program focused on a small number of space systems for communications and an even smaller number for tracking and did not accumulate capabilities over multiple missions, instead opting for single site sorties. NASA's new lunar mission set, composed of a combination of human exploration elements forming the Artemis campaign and science elements through a recurring set of CLPS missions, changes all three of those key parameters. A multi-element international Gateway will be established in lunar orbit, functioning similarly to the ISS in LEO. An ABC will be established near the lunar south pole with a steady expansion of base capabilities and increasing excursion range with robotic and crewed rovers. CLPS missions will deliver a steady stream of science and technology payloads to destinations all over the Moon, including the far side. The aggregate downlink demand from these missions with tens of space systems is estimated to reach ~1 gigabit per second (Gbps) by 2030. The uplink demand, unlike the typical tens of kilobits per second (Kbps) needed to command robotic spacecraft, is estimated to reach tens of Mbps (i.e., three orders of magnitude greater than current capability), which, like the ISS, is largely required for human crews.

These factors drive defining a new architecture for the Moon: LunaNet, a lunar Internet capable of starting small but growing over time, providing the communications and navigation infrastructure to support the steadily growing demand. Like the Internet, LunaNet will be composed of contributions by many organizations. No one organization will own or control it. It will act as a single, integrated network by virtue of standardized services and interfaces enabling international interoperability. Figure 7.2-1 lists some of its key characteristics and provides a notional diagram of the extent of the networks that include Earth-to-lunar orbit, lunar orbit-to-lunar orbit, lunar orbit-to-lunar surface, and lunar surface-to-lunar surface links. Network layer services using the Internet Protocol and Bundle Protocol for delay/disruption-tolerant networking will make LunaNet operate like our terrestrial Internet. Navigation services, including traditional deep space radiometric tracking, will be combined with navigation broadcast service similar to the US global positioning system and European Galileo systems using highly accurate clocks to provide highly accurate position and orbit determination.

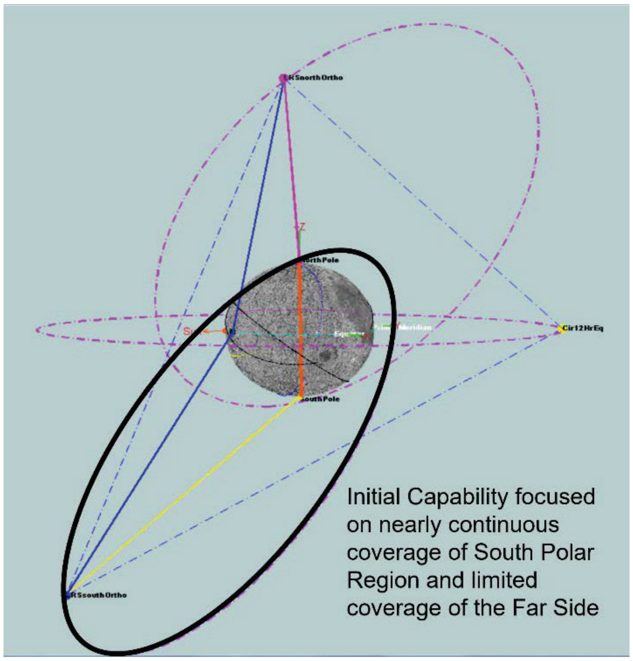


- *LunaNet is the lunar Internet – a set of cooperating networks providing interoperable communications and navigation services for users on and around the Moon.*
  - Based on a framework of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability
  - Allows many mission users to benefit from services of diverse commercial and government service providers
- **Service-Oriented:** Services include data transmission; Position, Navigation, and Timing (PNT); and situational awareness information
- **Scalable**: Introduce minimal capability for earliest missions and expand as needed for new users and service providers
- **Open**: Based on open international standards like the Internet
- **Resilient**: Resilience to failures and outages increases as networks grow
- **Secure**: Protect sensitive data while preventing or rapidly recovering from cyber threats
- **Extensible**: Apply the LunaNet concept to any planetary body

Figure 7.2-1. LunaNet Overview and Key Characteristics

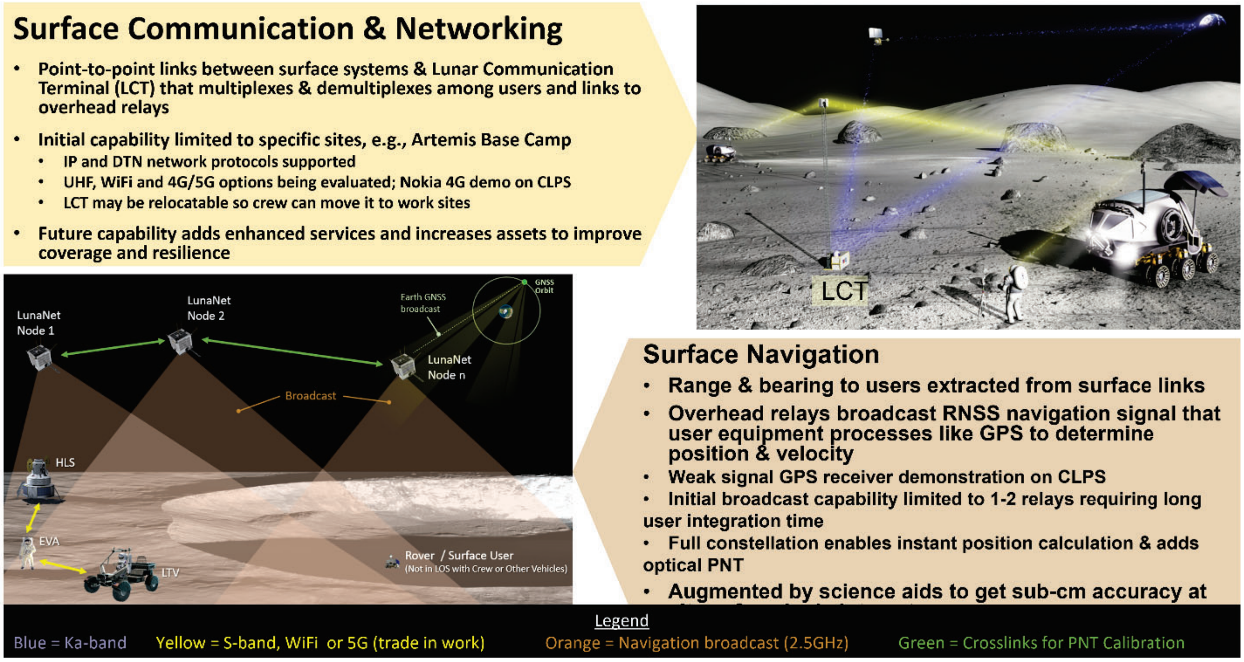
Achieving LunaNet requires adding lunar communication and navigation satellites to provide polar and far side coverage. Figure 7.2-2 shows the preferred concept for an early network of relays using elliptical lunar frozen (ELF) orbits. Relays in the southern ELF orbit (black) provide early coverage of the south polar region and periodic far side coverage. The same orbit with a northern inclination could be used to add coverage of the north polar region and increase far-side coverage, while equatorial relays could be added to provide nearly complete and continuous lunar coverage. The number of relays in these orbits could be increased to enhance capacity. In addition to communications and networking, these satellites would provide radiometric tracking to assist in landing, ascent, and surface mobility.

On the lunar surface, a similar combination of capabilities in addition to the orbiting LunaNet capabilities will provide robust communications, networking, and navigation services to robotic and human users, as shown in Figure 7.2-3. The navigation broadcast signal will provide coverage into permanently shadowed regions (PSR) to support surface mobility for *in situ* resource utilization (ISRU) and geological research.



Initial Capability focused on nearly continuous coverage of South Polar Region and limited coverage of the Far Side

Figure 7.2-2. Candidate Orbits for Early LunaNet Constellation



Surface Communication & Networking

- **Point-to-point links between surface systems & Lunar Communication Terminal (LCT) that multiplexes & demultiplexes among users and links to overhead relays**
- **Initial capability limited to specific sites, e.g., Artemis Base Camp**
    - **IP and DTN network protocols supported**
    - **UHF, WiFi and 4G/5G options being evaluated; Nokia 4G demo on CLPS**
    - **LCT may be relocatable so crew can move it to work sites**
- **Future capability adds enhanced services and increases assets to improve coverage and resilience**

Surface Navigation

- **Range & bearing to users extracted from surface links**
- **Overhead relays broadcast RNSS navigation signal that user equipment processes like GPS to determine position & velocity**
- **Weak signal GPS receiver demonstration on CLPS**
- **Initial broadcast capability limited to 1-2 relays requiring long user integration time**
- **Full constellation enables instant position calculation & adds optical PNT**
- **Augmented by science aids to get sub-cm accuracy at**

Legend

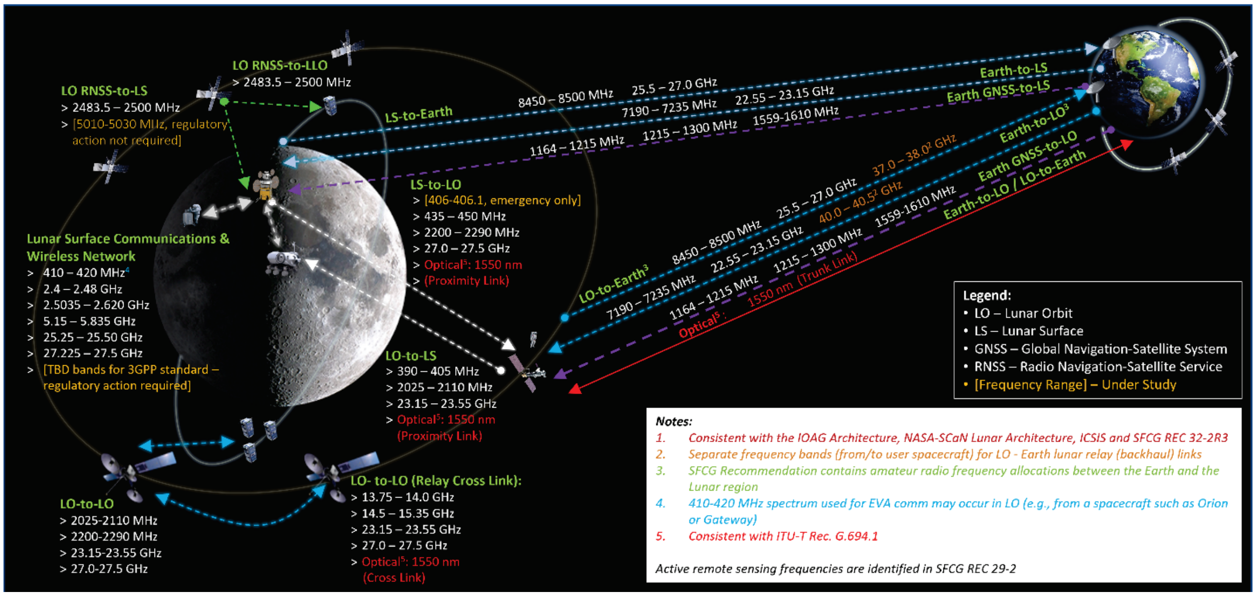
Blue = Ka-band Yellow = S-band, WiFi or 5G (trade in work) Orange = Navigation broadcast (2.5GHz) Green = Crosslinks for PNT Calibration

Figure 7.2-3. Lunar Surface Communications, Networking, and Navigation Capabilities

To achieve these capabilities, a lunar spectrum architecture has been developed by the Space Communications and Navigation (SCaN) Program in coordination with NASA's Spectrum Management Office. As shown in Figure 7.2-4, this architecture include the RF uses, as well as growth for future optical communications and navigation services. The frequency bands have been reviewed for compliance with the United Nations' International Telecommunication Union (ITU) and Space Frequency Coordination Group (SFCG) protections for the shielded zone of the

Moon (SZM), as described in Section 7.3. Fundamentally, the architecture restricts use of all bands below 2 GHz to minimize potential radio astronomy RFI. S-band (2-GHz) services are used for lunar proximity links (i.e., those links between lunar orbiting and surface systems), while X-band (8 GHz) is used for telemetry, tracking, and control (TT&C) links from Earth along with medium rate mission data. This separation of S- and X-bands is due to the increasing congestion being experienced globally in S-band. UHF in the 410- to 420-MHz band is authorized for use for EVAs; however, this is expected to be constrained to use either in locations where or at times when radio astronomy is not being done. Amateur radio is allocated use of the 144- to 146-MHz and 435- to 438-MHz bands, which will only be used on the near side. Use of 5G cellular telephony capabilities, based on standards developed by the 3rd Generation Partnership Project (3GPP), is being considered for surface use in addition to WiFi®, but the associated frequency allocation is still under study. Optical capabilities use 1550 nm, equating to 193 terahertz (THz), which does not present any concern for radio astronomy.

The navigation broadcast signal is allocated to the 2483.5- to 2500-MHz band recently approved by the SFCG for this purpose. In addition, the L-band used by the terrestrial Global Navigation Satellite System (GNSS) (i.e., 1164 to 1215, 1215 to 1300, and 1559 to 1610 MHz) is used in receive-only mode as a means of synchronizing the terrestrial GNSS (including time dissemination) with the LunaNet equivalent navigation broadcast.



Legend:

- LO – Lunar Orbit
- LS – Lunar Surface
- GNSS – Global Navigation-Satellite System
- RNSS – Radio Navigation-Satellite Service
- [Frequency Range] – Under Study

Notes:

1. *Consistent with the IOAG Architecture, NASA-SCaN Lunar Architecture, ICSIS and SFCG REC 32-2R3*
2. *Separate frequency bands (from/to user spacecraft) for LO - Earth lunar relay (backhaul) links*
3. *SFCG Recommendation contains amateur radio frequency allocations between the Earth and the Lunar region*
4. *410-420 MHz spectrum used for EVA comm may occur in LO (e.g., from a spacecraft such as Orion or Gateway)*
5. *Consistent with ITU-T Rec. G.694.1*

Active remote sensing frequencies are identified in SFCG REC 29-2

Figure 7.2-4. RF and Optical Spectrum Architecture for Lunar Region Communications and Navigation

7.3 Preserving the Radio Quiet Environment of the Moon

The far side of the Moon presents a unique opportunity for low-frequency radio astronomy. This has been recognized and codified in the ITU radio regulations, creating the SZM as depicted in Figure 7.3-1. Regulations in place to protect the SZM include the ITU Radio Regulations, the SFCG recommendations, and, in particular, International Astronomical Union (IAU) Resolution B16:

- ITU-R REC RA.479-5 (2003), ITU-R REC RA.769-2 (2003).
- SFCG Recommendations 32-2R3 and 29-2, SFCG Resolution 23-5.

Figure 7.3-1. Shielded Zone of the Moon (SZM)

RFI can corrupt desired science measurements. When RFI does occur, it is difficult to correct or compensate for, so data are often flagged as simply lost. Passive sensors and radio astronomy systems are particularly sensitive to RFI because they are designed to detect very weak RF signals.

NASA is actively involved in domestic and international coordination forums to ensure protection of spectrum for passive remote sensing and radio astronomy applications, including maintaining the SZM free from RFI for its value for passive observation, while recognizing the requirement for radiocommunication transmission in support of science objectives (essential transmissions).

The frequencies being observed by the proposed low-frequency radio telescopes are lower than typically used for spacecraft communications, so the major concern with maintaining the SZM is with broadband radio emitters (e.g., high-power switching circuits, motors, and digital noise from computers).

F-3. The frequencies being observed by proposed low-frequency radio telescopes are lower than typically used for spacecraft communications, so the major concern with maintaining the SZM is with broadband radio emitters (i.e., high-power switching circuits, motors, and digital noise from computers).

R-2. Adequate low-frequency RFI testing, screening, and shielding must be considered for all spacecraft and payloads that will be visible from the lunar radio quiet zone. Spacecraft equipment destined for the SZM must be designed to standards to minimize RFI and be subjected to radio noise validation tests.

7.4 Extreme Thermal Environment

The lunar thermal environment presents a difficult engineering challenge due to the extreme variation in temperatures from lunar day to night. Exposure to these temperature extremes may compromise the performance of conventional electronics and thermal control systems. Additionally, induced thermal gradients can cause high thermal stresses and structural fatigue. These extremes are primarily due to the Moon's lack of atmosphere, its slow rotational period, and the low thermal diffusivity of the regolith. Surface temperatures can vary from 18 kelvin (K) in the coldest lunar craters [Paige and Siegler, 2016] to above 400 K near the equator [Williams et al., 2017], which is one of the widest ranges for rocky bodies in our solar system. As shown in Figure 7.4-1, these temperature swings occur nearly everywhere on the surface. The lunar day/night cycle lasts 29.5 Earth days, with maximum surface temperatures occurring around local noon, and minimum temperatures occurring just prior to sunrise.

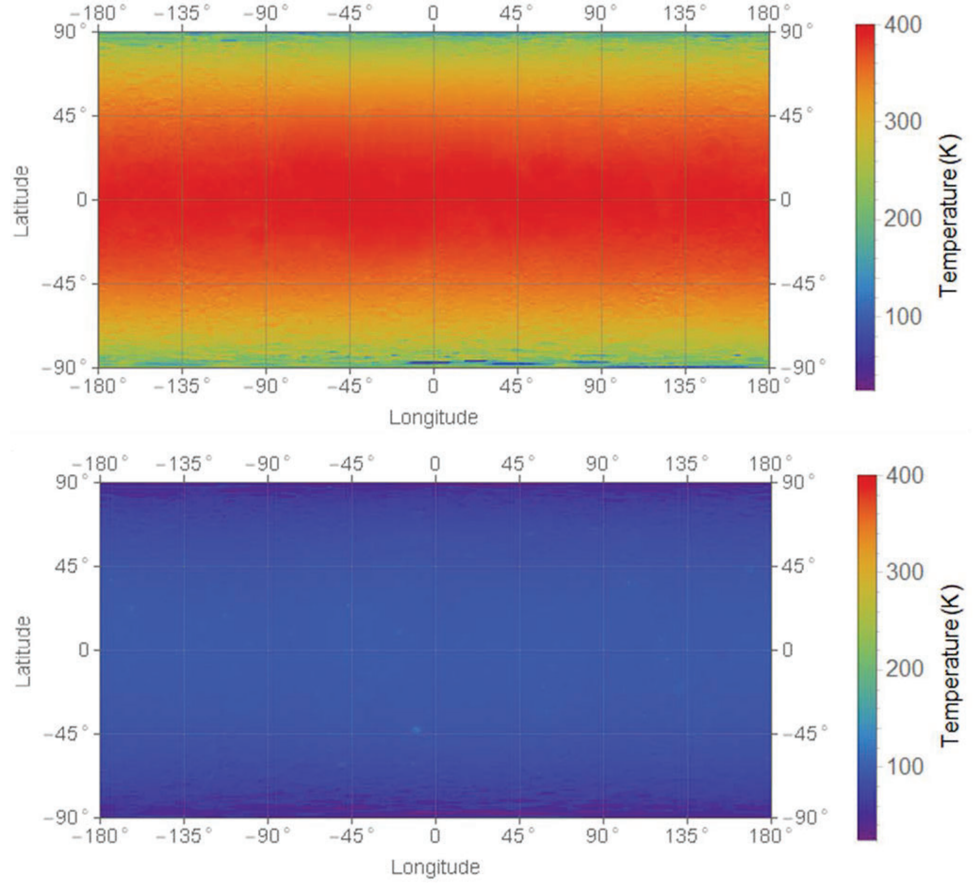


Figure 7.4-1. Maximum (top) and Minimum (bottom) Global Temperatures

An object sitting on the lunar surface will exchange heat with the regolith through conductive and radiative heat transfer and will experience solar heating via direct incident sunlight and sunlight reflected off the regolith (albedo). Direct solar radiation varies from 1310 to 1426 watts per square meter (W/m^2), depending primarily on the distance from the Moon to the Sun. Reflected solar radiation varies from 91 to 285 W/m^2 depending on regolith reflectance, which can range from 0.07 to 0.2. Regolith reflectance can vary due to regolith composition and solar incidence angle. The IR radiative heat flux from the surface can be as high as 1255 W/m^2 depending on regolith temperature and emissivity, which can range from 0.95 to 0.98

[SLS-SPEC-159, 2021; HLS-UG-001, 2021]. It is worth noting that an object can receive as much energy from the lunar surface (IR and albedo) as it does from direct solar heating.

For the lunar radio telescope case studies examined in this workshop, the potential landing sites are on the far side of the Moon roughly between –60° and +60° latitude and 120° and 240° longitude. These missions desire to survive or operate during the lunar night with a potential operational life of 5 years or longer. Therefore, they will experience multiple day/night cycles and see the full range of extreme temperatures at their locations. Zonal mean temperatures in this region can range from 82 K to 391 K with extremes from 70 K to 405 K. Temperature differences between the far and the near sides are not significantly different, with equatorial temperatures on the near side averaging around 3 K warmer at noon compared with those on the far side [Williams et al., 2017] This is due to the higher prevalence of maria regolith on the near side, which is less reflective in the solar spectrum than highlands regolith, which is more prevalent on the far side [SLS-SPEC-159, 2021; HLS-UG-001, 2021]. However, this effect is somewhat offset by the fact that the far side of the Moon is closer to the Sun at local noon than the near side; therefore, it receives about 1% more solar flux [Kaczmarzyk et al., 2018].

Local surface temperature variations can also present a challenge as regolith temperatures can vary drastically even across small distances. These variations can be due to terrain topology and regolith composition. Terrain features like hills and craters can affect solar visibility and azimuth, resulting in hot spots. Similarly, shadowed areas can be significantly colder than their illuminated surroundings. Seasonal variations also affect surface temperatures, although in general they are only significant at the poles due to the Moon's small axial tilt of 1.5° relative to the ecliptic plane [Williams et al., 2019].

The presence of dust will also degrade the performance of radiators, further exacerbating the thermal management challenges. Dust impacts on radiator performance have been studied using regolith simulants [Gaier et al., 2010, 2013], and dust mitigation and removal technologies are in development. However, more work is needed to better understand the impact of lunar regolith dust as a function of coverage, especially for other types of thermal control surfaces (e.g., specular reflectors or insulation).

Continued research and development in thermal technologies for surviving the extreme lunar environment will expand the range and capabilities of lunar surface missions. The NASA STMD recently published an overview of the current state of the art, new advances, and goals for future development of such technologies [STMD, 2022].

7.5 Power Generation and Storage

The surface of the Moon poses a unique set of challenges for missions not found elsewhere in the Solar System. This section discusses the primary engineering challenges faced by lunar surface missions and their impact on current state-of-the-art power generation and energy storage systems and provides a short discussion on power distribution challenges.

7.5.1 Lunar Surface Challenges

The primary engineering challenges experienced by lunar surface missions are the result of the environment on the lunar surface. In particular, the extreme thermal environment and the impact of lunar dust will drive designs of the power generation and energy storage systems. These environments will be briefly discussed here as they relate to the power generation and energy storage systems, but a full discussion can be found in their respective sections of this report.

Perhaps the most challenging issue is the length of the lunar diurnal cycle, with a mean length of 29.53 Earth days, which results in a point on the lunar surface being illuminated for roughly 14.75 Earth days and shaded for the same duration. This, along with the low thermal conductivity and high emissivity of the lunar regolith, produces temperature extremes during both the lunar day and night. Surface temperatures around the equator can vary from up to 400 K during the day and down to 80 K at night, with local variations based on surrounding topology and geologic features. The highlands that dominate the far side of the Moon generally have a higher albedo, which reflects more of the solar thermal radiation, resulting in a slightly lower maximum temperature.

The impact of the extreme diurnal temperatures generally has a negative effect on power generation. The high daytime temperatures increase degradation of components and reduce efficiencies of many power-generating systems. The large gradient between day and night temperatures generates thermal stresses in components and typically requires active heating to maintain operational temperatures through the night. This requires power to be available at all times, which can greatly increase the mass and complexity of the energy storage systems due to the long lunar nights.

The other challenge discussed here is the impact of lunar dust on power generation systems. Typical state-of-the-art power generation systems (e.g., solar arrays and radioisotope power systems (RPS)) are reliant on large external surfaces to generate power. Should these surfaces experience dust deposition, their effectiveness may be greatly reduced, typically requiring the design to carry margin, which increases cost and mass. The long-term effects of dust on sensitive surfaces are relatively unknown, as the last NASA lander mission was Apollo 17 in 1972. More detail on the dust effects related to specific technology is provided in Sections 7.5.2 and 7.5.3.

7.5.2 Power Generation Technologies

This section briefly discusses three primary power generation technologies being considered for lunar surface application (i.e., photovoltaic array, RPS, and fission power systems) and the environmental impacts for each.

Photovoltaic arrays, or solar arrays, are one of most common technologies used to generate power on space-based systems. Solar arrays are composed of multiple photovoltaic cells, which are made from semiconductor wafers that produce power when exposed to light. The amount of power generated is determined by the intensity of the solar flux on the surface of the solar array. This is maximized by ensuring the array is pointed directly at the Sun, typically requiring mechanisms to orient the solar arrays. Benefits of using solar arrays to generate power on the lunar surface include the maturity of the technology, scalability, and length of the lunar day. Solar arrays have been used on the majority of space vehicles and are well characterized for the space environment and integration onto vehicles. They are easily scalable by increasing the number of solar panels in the array to fit the needs of the mission. The long lunar day provides extensive periods of power generation to enable science and energy storage charging to prepare for the night. The challenges with using solar arrays include:

- The system must include energy storage to provide power to the mission throughout the lunar night.
- Extreme temperatures reduce array efficiency and increase degradation of the photovoltaic cells.

- Articulation is required to maximize the array effectiveness.
- Mitigation of dust accumulation is necessary.

The second technology is the RPS. These systems use heat produced by the natural decay of plutonium-238 (Pu-238) to generate power. Current systems use static thermoelectrics to convert a heat gradient to power. There is currently a dynamic system in development that will use Stirling engines to generate power at a higher efficiency. These systems use Pu-238 on the internal, hot side of the RPS and radiator fins on the external, cold side. The amount of temperature difference determines the amount of power produced. Currently, there are multiple missions using RPS as a power source, including Voyager 1 and 2, the Mars Curiosity and Perseverance rovers, and the New Horizons mission. The Apollo Lunar Surface Experiments Package (ALSEP), which was a set of experiments on the lunar surface as part of the Apollo missions, was powered by the SNAP-27 RPS and was set up by the Apollo astronauts. RPS are designed to operate for extended periods of time and can generate power during the lunar day and night, eliminating the need for significant energy storage systems. Some of the challenges faced by RPS missions are the high temperatures on the lunar surface during the day, which reduce the temperature difference across the power conversion system, resulting in reduced efficiency. Additionally, lunar dust deposition on the radiators will increase the solar absorptivity of the radiators, reducing their effectiveness while illuminated. RPS missions are typically under 1kWe, but this can be scaled with multiple RPS units.

The final power-generation technology is fission power systems. Unlike the natural heat of decay used by an RPS, fission systems use a uranium reactor to provide the power conversion system with heat. This fills the role for power level requirements higher than can be generated by an RPS, with current concepts in the 1 to 10 kWe range and up to 40 kWe. The systems currently in design use low enriched uranium (LEU) to provide the fissile material to the reactor, controlled via control rod. Current power conversion systems being looked at are Stirling engines and Brayton cycle engines. Many of the same benefits and drawbacks as for the RPS are applicable to fission power systems as well, with fission systems being able to generate power throughout the day and night. Fission systems are less susceptible to the high lunar surface temperatures because they can run higher radiator temperatures. An additional drawback to fission systems is the need to protect sensitive nearby objects from the radiation produced. This requires shielding on the reactor itself or use of the surrounding environment or distance to shield users.

Missions using RPS or fission systems are required to go through the NASA Nuclear Launch Authorization process, which is NASA's process to ensure the safety of the public during launches containing nuclear material.

There is no one-size-fits-all approach to choosing a power generation technology for lunar surface missions. Each mission will need to address their requirements while weighing the pros and cons of each type of technology.

7.5.3 Energy Storage

The lunar diurnal cycle poses a difficult challenge for energy storage systems. Excluding the extreme cases near the poles, a lander on the surface of the Moon will experience roughly 14.75 continuous Earth days in the dark, as well as extremely cold surface temperatures. An energy storage system must be sized to provide the required operational or survival power throughout the lunar night. Many missions choose to limit operations during this period to only what is required to survive to minimize the size of the energy storage system. One of the benefits of fission and RPS systems is that they can operate and provide consistent power levels throughout the night, potentially allowing more than just survival operations to be performed and providing a source of heat on the spacecraft itself.

Many current missions use batteries as the core of their energy storage system. Many potential battery cell chemistries have been well-characterized and can be scaled to meet the needs of a given mission. Many missions are using lithium-ion cells, which can achieve a high energy density. One of the drawbacks to lithium-ion batteries is the need for a more complex power management system and charge controller, which reduces the system energy density. Additionally, lithium-ion batteries require a thermal management system to maintain them within their optimal temperature range for safety, as well as voltage stability and cell degradation.

Another energy storage technology currently under development is regenerative fuel cells (RFCs). RFCs use a fuel and oxidizer that are reacted in the fuel cell to produce energy and the resulting byproduct of the reaction. During the lunar day, when external energy is available via solar panels or similar, the reactant byproduct is electrolyzed to separate the byproduct into its initial fuel and oxidizer constituents to be stored until energy is needed. RFCs can self-generate heat when supplying energy, which can be a benefit during the lunar night, saving potential heater power for other systems. RFCs have relatively complicated supporting systems to transport the reactants and byproduct to the storage tanks and electrolyzer cells. While fuel cells have flown in the past on Shuttle missions, there is currently no flight-qualified system. Many fuel-cell chemistry options are currently operating in the terrestrial market. Several have good aerospace viability, particularly the low-temperature proton exchange membrane (PEM) and high temperature solid oxide fuel cell (SOFC), which are currently being developed for aerospace applications.

7.6 Lighting

The lighting environment on the Moon is different enough from that on Earth that it demands special consideration in designing for human interaction. It will be important to plan work based on the natural lighting conditions and their effect on the visual envelope of the people (or robots; see below) who must perform the required work. Near the poles all the time, and for several Earth days each month, in the middle latitudes the Sun will be near the horizon. there will be extreme glare if the workstation has the astronaut facing in the direction of the Sun. This glare is likely to make identification of the components to be worked on and interaction with its fasteners and connectors nearly impossible. If the Sun is overhead (middle latitudes), there still could be glare from structures and from regolith, and while this is more manageable than looking into the Sun it should be considered in worksite design. In any case, consideration should be made for artificial lighting, even when the system is in daylight, because shadows from structure or terrain could put the task components into extreme darkness. The EVA system will include lights, so designers must understand their capabilities and make decisions about whether the provided illumination will be sufficient. If not, the instrument design team may choose to provide special task lights. Despite the issues identified, the lighting environment at these latitudes is benign and is easily compensated for relative to the natural lighting environments at the poles.

7.6.1 Special Case of Lighting at the South Pole

This special case should be discussed because NASA's current human exploration plans are for destinations near or south of the Lunar Antarctic Circle. The south polar region has many areas of rugged terrain of mountains and craters. Since the Sun is at low angles, meaning its rays are nearly tangential to that part of the sphere, the shadows are extremely long and cover large areas of the surface. The Sun, if visible at all, will present significant glare issues whenever an astronaut or robot is facing in its general direction. Elsewhere, there will be little reflected light in the large, shadowed areas. These factors will require designers to understand these conditions in much greater detail than in the middle latitudes.

8.0 Human/Robotic Lunar Science Exploration in the Artemis Era

The Artemis Program of exploration promises to enable significant progress in the scientific exploration of the Moon and eventually Mars. Since the beginning of the space age, scientific discoveries have been made by a partnership of humans and robots. As noted by Clancey [2006], robotic spacecraft do not discover anything, people do. With the renewal of robotic precursor landers and rovers on the Moon, followed by astronaut sorties on the lunar surface, progress in the scientific exploration of the Moon will generate many new and exciting discoveries.

8.1 Enabling Science

While the initial science will be focused on lunar science, the combination of robotic and astronaut capabilities, especially when working together, offers the opportunity to expand the scientific utilization of the Moon to include topics in heliophysics, Earth observation, and astrophysics. As a corollary to lunar planetary science, the human-robotic partnership will also be a powerful enabler of the research required and the realization of ISRU. The power of a well-trained astronaut working in a spacesuit on the surface or on site in a well-equipped lab cannot be understated. The human ability to observe, imagine, and react to real-time and often unexpected situations is often when the greatest discoveries are made.

There are many new capabilities planned for the Artemis Program, including launch of the Space Launch System (SLS) rocket, CLPS delivering science to the Moon's surface, the human-tended Gateway station in a high rectilinear lunar orbit, the Orion capsule, and the eventual establishment of the ABC on the Moon's surface. Although robotic precursors will precede human exploration, they will be controlled (supervised autonomy at best) by human operators. As humans venture further from Earth, the most effective partnership of humans and robots will be to move that robotic control along with the human explorers, as well as the use of robotic precursors and missions where people will not venture. This will require interfaces and operational procedures to best take advantage of the strength of the on-site human-robotic partnership.

O-5. In the near future, there will likely be increased cooperation between human and robotic exploration.

There is no debate that human spaceflight has contributed significantly to science. One only has to look at the amazing scientific record of achievement of the HST, enabled by the five servicing missions to upgrade and repair the observatory. The success of these missions was dependent on highly trained and skilled crew and, in particular, their ability to respond to anomalies in real time using the marvelous human brain to creatively solve problems. The HST servicing missions are examples of human spaceflight enabling great science. In some instances (e.g., the early Apollo missions), the prime motivation for the missions was not science, but decisions about the conduct of those missions were steered by the desire to have a productive scientific program, even if of limited ambition. This may be the case for the early Artemis missions to the Moon. For the Apollo "J" missions, the scientific program was laid out well in advance, and the lunar rover capability vastly increased the ability of the astronaut to make scientific discoveries. These were science-driven missions, and they produced a bounty of scientific results. In all these cases, a critical element to the success of the missions was the extensive training of the astronauts to be able to execute their activities on site, including science training. The mission plans were developed by a large team, including the operations team, the flight crew, the science teams, management, safety, and others.

8.2 The 2023-2032 Planetary Decadal Survey

Given the nascent development in Artemis, how can the Artemis exploration enable science from the Moon in the early missions, and how can a science-driven approach affect the architecture plans for the long-term Artemis exploration of the Moon? The 2023-2032 National Academy of Sciences Planetary Decadal Survey (PDS2023) considered this issue [PDS2023, 2022]. It is the first planetary science decadal report that takes on the issue of how to ensure that the human exploration of the Moon and Mars generates "decadal level" science. PDS2023 notes that human exploration is aspirational and inspirational, and NASA's Moon-to-Mars plans hold the promise of broad benefits to the nation and the world. A robust science program provides the motivating rationale for sustained human exploration. The advancement of high-priority lunar science objectives should be a key requirement of the Artemis human exploration program.

PDS2023 finds that a strong science program should drive planning and execution for a strategic program to accomplish planetary science objectives for the Moon, with an organizational structure that aligns responsibility, authority, and accountability. PDS2023 goes on to recommend that the SMD should have the responsibility and authority for integrating Artemis science requirements into the overall Artemis architecture, including human exploration capabilities.

The PDS2023 examined two rover options for studying the South Pole Aiken Basin, the highest priority lunar science with the potential to revolutionize our understanding of the Moon and the history of the early solar system. After deliberating on a robotic traverse and sample return, which could result in several kg of samples being studied back on Earth, and an astronaut-assisted rover mission, which has the potential to return 100+ kg of samples, PDS2023 endorsed the astronaut-assisted variant, Endurance-A, as the highest priority for the Lunar Discovery and Exploration Program. The Endurance-A mission would, as described in the NASA SMD-sponsored studies:

- Use CLPS for delivery to the lunar surface.
- Collect 100 kg or more of robotically acquired samples in a ~1000-km traverse across diverse terrains in the South Pole Aiken Basin.
- Deliver the samples to the ABC near the south pole of the Moon, for return to Earth by astronauts.

Coordination of these goals with Artemis provides an outstanding opportunity to expand the partnership between NASA's human and scientific efforts at the Moon. This example highlights the comparison of two missions of approximately the same cost (medium class planetary mission) and how the astronaut-supported version would return two orders of magnitude more science.

O-6. The workshop participants concurred with PDS2023 findings and recommendations regarding NASA's Organizational Structure for Incorporating Science into Human Exploration**.**

8.3 Worksite Design

Examples of the EVA successes of working weightless in a vacuum are significant. As stated above, on five successful HST servicing missions, NASA demonstrated the utility and adaptability of humans working in spacesuits on astronomical instruments. These astronauts have manipulated interfaces, ranging from standard circular Amphenol connectors, and LEMO, SMA, odd unique interface, and mechanical connections. On the 2009 HST mission, crewmembers were even able to do board-level repairs while working in the spacesuit. After the Apollo missions, many of the astronauts indicated that the suits were great but the gloves needed fixing—NASA redesigned them, which led directly to the ability of the HST servicing astronauts to perform the delicate repairs. These spacewalking techniques have allowed NASA to reinvent the telescope on each mission and have allowed HST to perform science for more than three decades, with the mission continuing to this day. Most significant is that the utility of humans to use their brains *in situ* and adapt has been proven.

To enable astronauts to interact effectively with science investigations on the Moon, the capability for humans working in spacesuits (or for that matter in a shirtsleeve environment in a lab) must be designed into the experiment systems from the start. This maxim is important not only for maintenance, repair, and upgrades, but also to optimize the conduct of the science.

The HST is a useful example of a science system that has been kept operational through human intervention. The system was designed to allow access by astronauts in EVA suits to facilitate expected technology improvements in instruments over time, enabling new observational capability. The HST was also designed to facilitate repairs and upgrades to the avionics and systems. The HST Program was designed for those activities over the lifetime of the telescope. Some of the new instrument development work for future missions were started many years before their flight opportunity. The design of the telescope included features and interfaces (i.e., doors and latches) to allow humans in cumbersome spacesuits to fit into the interior volumes of the telescope where work needed to be performed. Consideration was given to the astronauts "work envelope" to enable them to perform the required work tasks. These tasks included operation of tools to release fasteners, demating of connectors, and removal of components through a defined (designed) volume of the telescope that was kept clear of obstructions to enable this removal. The installation of a new instrument involved the same set of tasks in reverse. These features had to be included in the original design by making decisions about which instruments would be changed out and then accommodating the required envelopes by keeping other systems out of the way. This was a significant packaging problem, but it was necessary to allow the evolution of the telescope throughout its life, ensuring that astronauts did not inadvertently damage components while performing upgrades.

The HST provides another example for instrument design consideration. In addition to the planned upgrade missions, the HST had to be repaired after reaching orbit. Some of the tasks for the repair had not been planned, so many of the components that needed replacement or modification had not been designed to provide the envelopes required. A classic example is the correction of the spherical aberration of the primary mirror, which was discovered only after launch of the telescope in 1990. The 1993 repair on the Space Shuttle was a heroic effort, on the part of both ground support and operations personnel and the astronauts who did the work. This proves that such efforts can be accomplished, if necessary, but the repair was far more expensive than the requested ground test that would have discovered the optical problems before launch. The point is that if instruments on the Moon are to be repaired, upgraded, or maintained after deployment, it is preferable to design for that capability from the beginning.

The basic consideration for ensuring a system can be maintained, samples can be retrieved, or an operator can interact with the system is that the relevant interfaces must be accessible and understandable to the person who will handle the interaction. For a science instrument on the lunar surface, accessibility includes the type of envelope requirements described above for the HST, as well as ensuring stable footing. That is, if an astronaut is to stand on the surface to perform work, then the worksite must be at an appropriate distance above the surface to enable comfortable access. The HST had an advantage over lunar operations in that worksites were approached while weightless, so astronauts could position themselves as necessary to work safely. Working overhead in a gravity regime (e.g., operating wrenches or mating connectors) is fatiguing and thus increases the likelihood of error. Similarly, squatting or kneeling can only be done for short periods. Both these work postures can be mitigated by portable platforms or seats, which must be designed. All items to be removed should have handles to allow the astronaut to remove the components without damaging adjacent parts and allow the replacement items to be handled safely (e.g., without breaking sensitive protrusions). If astronauts need to climb on structures to reach the worksite, then they will need appropriately designed (for suit constraints and low gravity) ladders and walkways, with fall protection. As for the HST, envelopes for suited access (to allow volume for suits with tool caddies and power and life support systems), reach (less than if the astronaut were unsuited), gloved hand, tool, and vision are needed. Visual envelopes are more constrained than is widely appreciated; astronauts cannot easily see their feet, and turning the head 90° only allows them to see the inside of the helmet. NASA STD-3001 articulates many of the standards for suited and unsuited crew members for reach, visibility, and other capabilities; these standards can be used to design systems.

While the types of robots that may be available to support human work on the Moon are unknown, the issues that robots deal with in performing work on a system are the same as those for humans (i.e., envelopes and access). That is, a robot can only reach those work areas that its arms and end effectors can reach without interfering with other structures. The robot needs tool envelopes and appropriately designed fasteners and connectors for the available end effectors. Finally, the robot must be able to see the worksite; in this case, robots have an advantage over humans and might use synthetic vision, using wavelengths outside the visible light spectrum. Nevertheless, it is unlikely a robot will be able to look directly into the sun and still perform well. Once again, if the work task is out of the reach of the robot, whether too elevated or in too tight a volume, some accommodation (e.g., a lift) may be needed.

O-7. Any human assembly of scientific instruments or observatories on the lunar surface should focus on items that cannot be affordably and technically implemented by robots.

8.4 Design for Maintenance and Upgrade

The ISS was designed to be assembled and serviced by spacewalking astronauts. Elements like common parts and captive bolts (which are part of EVA requirements) were included in the ISS development. This has enabled construction and routine maintenance of the vehicle, extending its lifespan well beyond that originally planned. One of the great successes of the ISS assembly (and

HST servicing) was the use of "standard" EVA interfaces. These enabled the station to be assembled and the equipment serviced using the minimum number of tools. The use of standard interfaces (e.g., 7/16-inch double height bolts) should be extended to Artemis hardware.

Programs like the Alpha Magnetic Spectrometer (AMS) did not build EVA requirements into the AMS design, but due to hardware failures, EVA was a needed intervention to sustain the mission. Unlike many of the ISS repairs, this was a huge effort to not only attempt repair but also emplace measures to protect the EVA crewmembers. The repairs were successful, but it should be noted that work of this nature increases both programmatic cost (money and time) and risk to both crew and mission success.

The HST is unique in that it had both planned and unplanned servicing over its life. The planned servicing set it up for easier additional unplanned servicing that might not have been as successful otherwise.

Whether the hardware is designed for human or robotic delivery and initialization, the human element should be factored into the design. Future repair, reuse, and recycle opportunities are much greater if the hardware is designed with EVA requirements from the beginning. By extending the focus beyond the desired plan of the hardware to also include the "what if," the design can be steered toward EVA inclusion. EVA expertise from NASA is available to actualize EVA capability into the design concept, thereby extending the life of the hardware and hopefully its opportunities as a whole in the Artemis era.

To ensure the integrity of the science, the system should be designed at the outset for the human work to be performed. This is accomplished by making decisions regarding which aspects of the observatory or station should be upgraded, maintained, or otherwise serviced. These subsystems must be placed where astronauts and robots can access them, and interfaces (e.g., fasteners, handholds, end effector grapples, and connectors) must be designed to include the envelopes required for servicing. The following system design considerations are recommended:

- Allow for human or robotic missions to work in conjunction on the lunar surface.
- Design payloads for upgrades.
- Use standard interfaces.
- Allow for and plan for learning from experience.
- Design for and allow limited servicing or replacement (as one would on Earth).
- Take advantage of the emplaced infrastructure (e.g., wireless data, high data rate communication).
- For known limited-life components, build for robotic servicing (e.g., detectors, coolers, refueling, rotating components).
- Develop robots whose speed and trafficability resemble terrestrial four-wheel drive vehicles so robots can work on the same timescale as human crewmembers.

Requirements and standards recommendations:

- Integrate requirements into Artemis now for projects that may be a decade or more away.
- Adopt standard interfaces to enable human/robotic interaction (i.e., develop interface control documentation (ICD).
- Tools should be treated as a critical element of assembly, servicing, and manufacturing.

For the Artemis program to be sustainable, including the long-term operation of science hardware and a base camp, these considerations must be incorporated into the system designs at an early stage of development.

R-3. To enable servicing, design of future observatories or instruments deployed or constructed on the lunar surface should follow the HST and ISS models, where standards are followed to make them astronaut friendly for servicing (e.g., standard bolt sizes, easily accessible electronics cards, avoidance of sharp edges).

8.5 Leveraging Artemis Era Infrastructure

The infrastructure essential for EVAs in the Artemis era should include a home base that provides crew a habitat, consumables recharge station, high-bandwidth communication relays, and rapid Earth return for safety. In early missions, the crew will need clear communications with Earth, and in both early and late missions crew should have access to communication with each other. The small time latency will not significantly affect collaboration between science teams and crew.

One of the areas to be developed for Artemis is the necessary communication and navigation systems. This system should include a lunar navigation system that can provide the crew with consistent communication and precise navigation. Navigation is needed for safety (i.e., return to home base or site for safe haven) and science. Geographic location on Earth is defined by two coordinates, latitude and longitude, which can give a specific location outside of a reference point heavily used in terrestrial science. Without a lunar navigation system, the science may not be as accurate, hampering the pace of scientific discovery. There are many different means to develop and deploy a suitable lunar navigation system.

If Artemis era missions are focused mainly on the lunar South Pole area, then crewmembers will be dealing with extreme lighting conditions (Section 7.6). These conditions will have oblique lighting angles with extreme shadows. Lunar regolith can be highly reflective, and darkness can last for months on end. Permanently shadowed regions are extremely dark and very cold (i.e., outside the nominal range of EVA operations of ±200 °F), and areas that remain in shadow for months on end can become extremely cold (Section 7.4). This will require development of new spacesuit technologies to keep the crew warm and the spacesuit materials operable, including materials that remain compliant and secure at cryogenic temperatures.

EVA advancements are needed to make the process of EVA easier. Less overhead and less risk for each individual EVA will enable more time devoted to the scientific or maintenance aspect of the spacewalk. This can be in-suit improvements in mobility, mass reduction, and center of gravity adjustments. Environment advances for shorter prebreathe, quicker depress/repress, and less vehicle overhead are other improvement areas. Hardware and software concepts (e.g., advanced electronic information delivery) as part of the suit system could increase crew autonomy and alleviate some of the more detailed communication with Mission Control on Earth.

While it is still early in Artemis campaign development, significant advancements toward filling the technology gaps are expected as the Artemis infrastructure develops. As the missions build upon one another, so will the technology. In particular, initial missions should be testing dust tolerance and mitigation to support the lifecycle of the hardware, both internal in the habitation infrastructure and external hardware that is constantly exposed to the harsh environment on the Moon. At all stages, ensuring the safety of the crew is paramount.

R-4. To ensure the safety of the crew on prolonged missions, early environmental testing should be conducted for life support system tolerances and hardware exposure impacts during initial Artemis missions.

8.6 Required "Sustained Presence" Capabilities

To enable EVA operations, a consistent resupply of consumables needs to occur. These consumables can be delivered from Earth, mined from lunar resources, or obtained through a combination of the two. A constant resupply of oxygen, water, and power are required. Spacesuits have a low tolerance for contaminants in the water, and decompression sickness risks increase with low oxygen quality, so high-quality pure water and pure oxygen are required.

Other manufactured consumable items currently utilized by EVA crewmembers are maximum absorbency garments (MAGs), in-suit drink bags, and thermal undergarments. For a sustained presence that limits the delivery of manufactured items from Earth, new technology must be explored, whether in waste collection, drink bag sterilization for reuse, or the ability to fully launder dirty clothes.

As discussed in required infrastructure, dust mitigation, communication, and navigation are all required for sustained operations. The capabilities of the ABC should increase over time as early missions transition from "frontier outpost" to semi-permanent facilities.

The ability for crewmembers to be mobile in both pressurized and unpressurized vehicles will be critical to continued exploration and will enhance science that needs to be positioned farther away from the environmental impacts of a human encampment, whether they are chemical, light, or radio noise. Outposts or "safe haven" concepts can allow a crew to extend their range farther afield and still be able to revitalize or repair their vehicle enroute to the worksite.

In the Artemis era of the 2030s and 2040s, the human-robotic lunar surface infrastructure will grow from relatively short human stays (less than a single lunar month) supported by surface-based robotic systems to longer duration stays with greater human and robotic capability. This effort begins with the establishment of an ABC in the south polar region (Figure 8.6-1). However, the Artemis era will also likely see objectives pursued that extend across the lunar globe. The Artemis era will allow science to be pursued in local detail through repeated visits and permanent stations, and through far-reaching expeditions to new and unexplored regions—including the lunar far side [NASA Artemis Plan, 2020].

In support of this new era in lunar science, an early human-robotic presence will establish fundamental capabilities for conducting repeated lunar surface landings and departures, including habitation, human mobility, EVA, surface power, communications, and navigation. A growing number of supporting logistical functions should also be established.

Supplying crews to both live and work on the lunar surface includes providing food, water, breathing air commodities, as well as staging, installing, operating, and maintaining a growing amount of available scientific equipment (e.g., science racks, instruments, tools).

Expanding from this initial state, however, one can envision the establishment of pressurized volumes that can serve as dedicated laboratory space for lunar scientists that are separately outfitted from the living quarters. More space for more equipment, and more shop capabilities to support the work. Larger scale research can be conducted with more and larger instruments, a wider array of analytical equipment and needed storage space; fabrication tools and supplies; access to more electrical power, and networking with other surface-based crews, robotic aids, and other remote science stations. A good historical example is the progressive buildup of research and support capabilities on Antarctica.

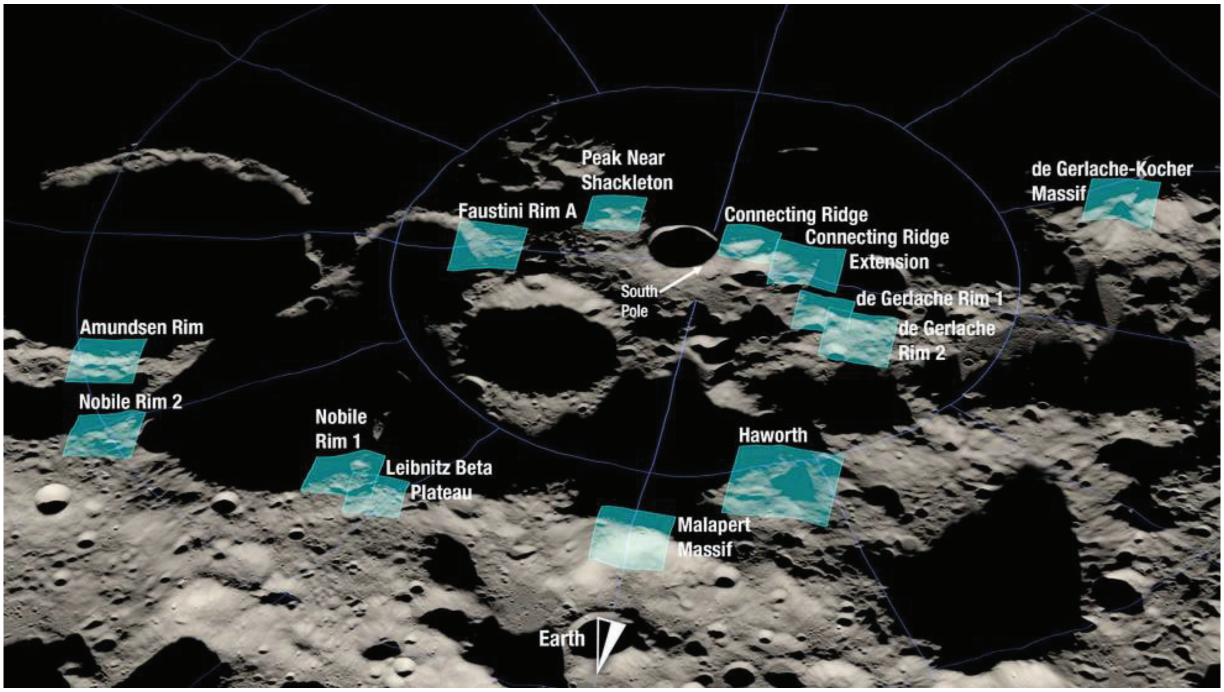


Figure 8.6-1. Potential ABC Locations about Lunar South Pole [reprinted from https://www.nasa.gov/press-release/nasa-identifies-candidate-regions-for-landing-next-americans-on-moon]

8.7 Artemis Architecture

NASA is employing a methodology that a) starts with the end in mind envisioning a sustainable and productive science enterprise, b) understands the initial capabilities and financial constraints of the government, industry, and academic partners, and c) analyzes the gaps in necessary infrastructure to achieve longer term objectives. This architecting from the right and executing from the left approach is shown in Figure 8.7-1, as it begins building the bridge to a new era in unique lunar science, technology, and research from the Moon [Free and Vogel, 2022].

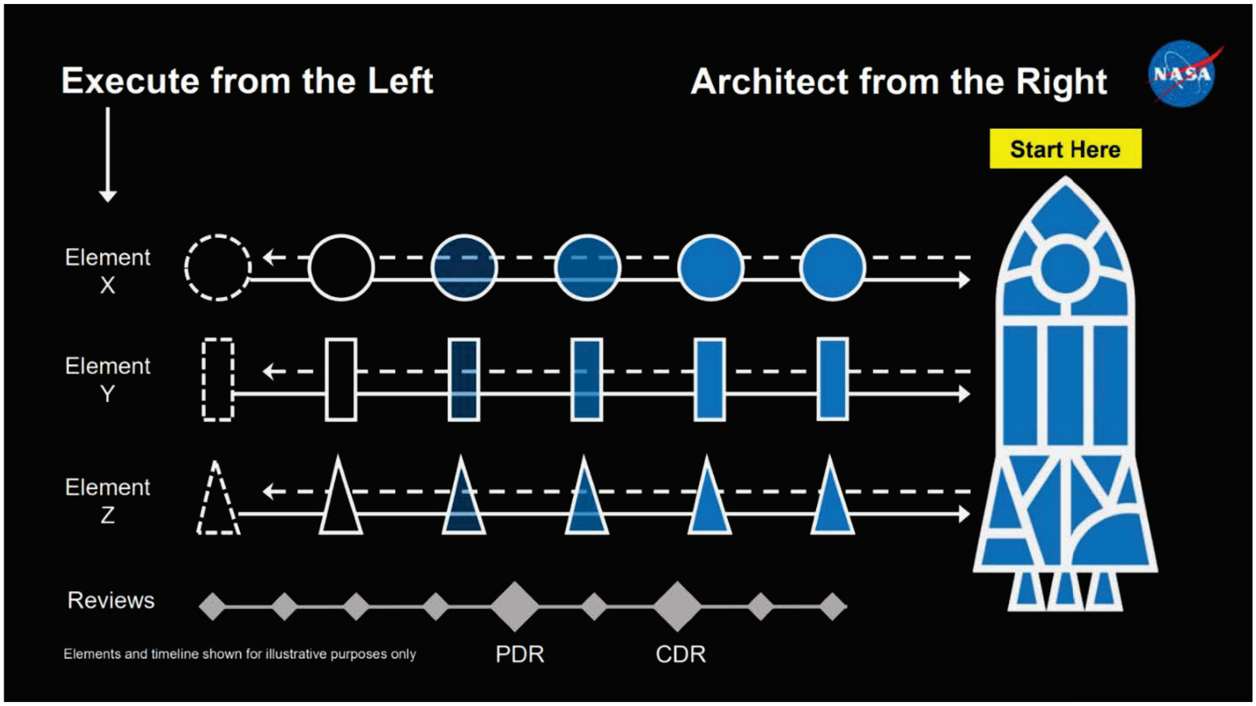
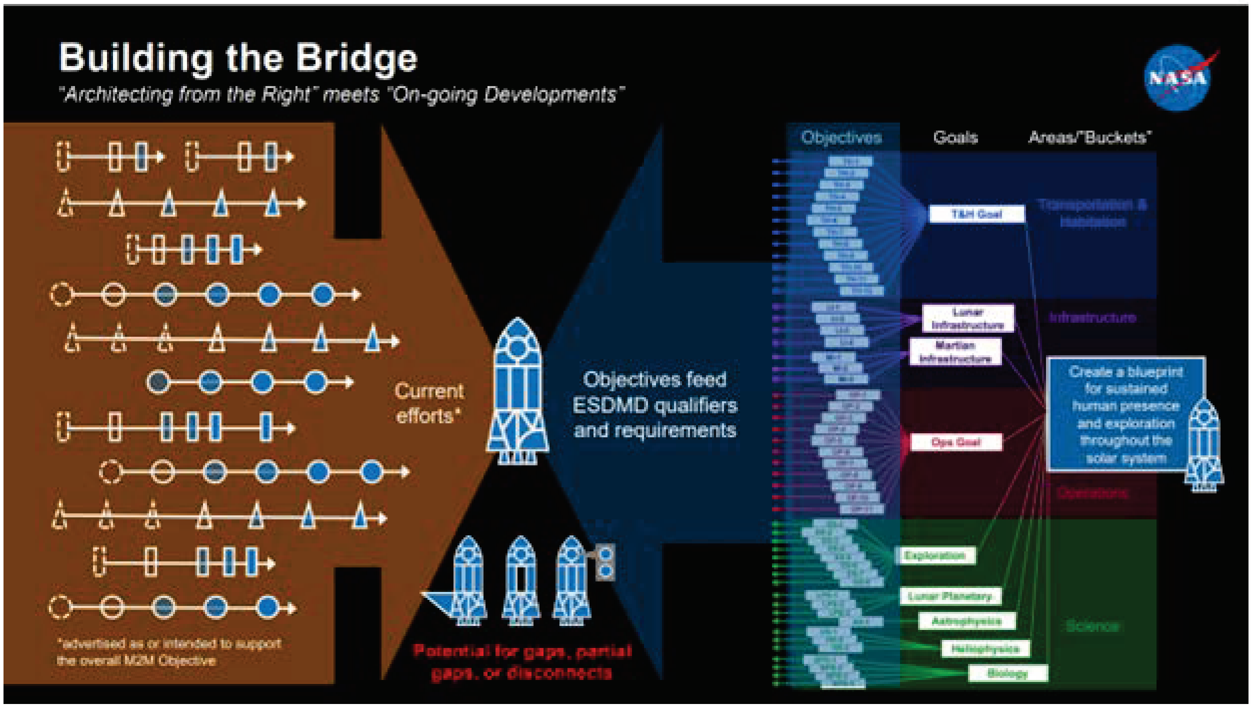


Figure 8.7-1. Lunar Element Architecture and Execution

The current Moon to Mars strategy emplaces many of the types of capabilities that will be needed to conduct unique human-robotic science from the Moon (Figures 8.7-2 and 8.7-3). These initial capabilities, to be available in the 2030s, will also help prepare for the first human missions to Mars. Common capabilities to be demonstrated include:

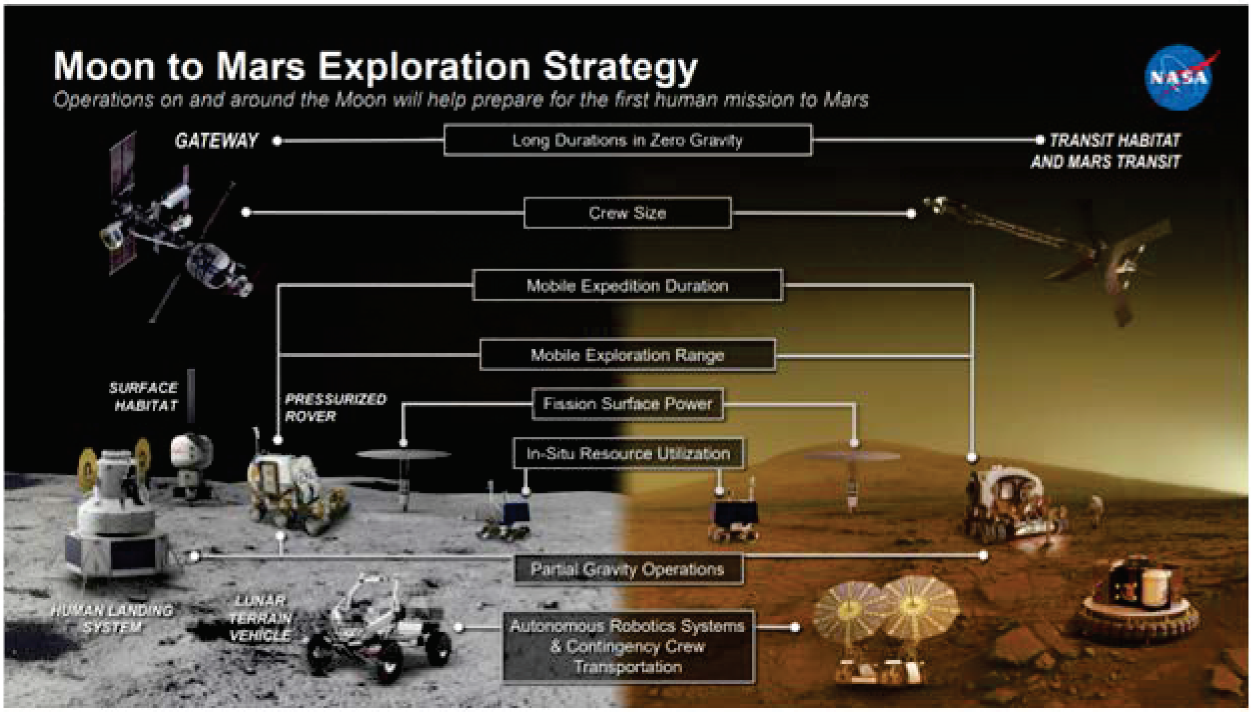
- Long durations for crews in zero gravity (lunar Gateway and Mars transit operations).
- Crew sizes amenable to conducting effective deep space missions.
- Mobile expeditions (range and duration).
- Fission surface power.
- ISRU at pilot plant scale.
- Partial gravity operations on the surfaces of other worlds.
- Some degree of autonomous robotic system activity with/without surface crews.
- Contingency methods and techniques employed across human-robotic systems.



Building the Bridge

"Architecting from the Right" meets "On-going Developments"

Figure 8.7-2. Methodology for Architecting Lunar Systems, Operations, and Infrastructure in the Artemis Ear (2030s through 2040s)



Moon to Mars Exploration Strategy

Operations on and around the Moon will help prepare for the first human mission to Mars

Figure 8.7-3. Moon to Mars Exploration Strategy—Operations on and Around the Moon Will Help Prepare for First Human Mission to Mars

Challenges come with south polar sites, from which human-based science capabilities will be based. The terrain around the south pole's Shackleton Crater, whose northwest rim is located on the geographical south pole, is rugged and offers only low incident angle sunlight and is in shadow for many months as the local terrain blocks the Sun during lunar obliquity swings; however, it also provides opportunities for relatively long durations of illumination. This is needed not only for visibility during operations but also provides the ability for solar power use and avoids very low temperature environments. PSRs are abundant and in many different sizes. This is both a science and utilization opportunity and an operational challenge to humans and machines.

Viewing maps of the lunar landscape can be deceiving in scale. Figure 8.7-4 shows the "metropolitan scale of the image, as well as the deceiving depth of a crater such as Shackleton" [Artemis Plan, 2020].

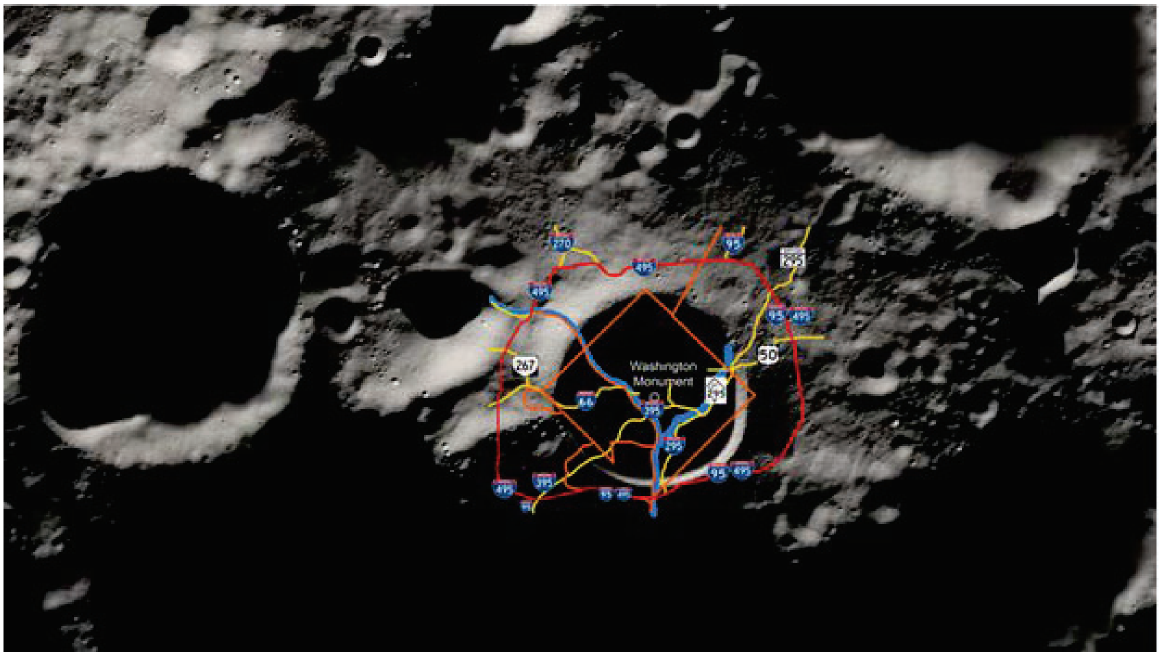


Figure 8.7-4. Lunar South Pole with Shackleton Crater

Surface operations and support functions were offered at the workshop (Figure 8.7-5) as a notional view of what might be included when architecting from the right (i.e., from the vantage point of the 2030s and 2040s). Some functions will emerge in the actual architecture as sited elements, others as shared elements, and other a hybrid combination of functions. The emphasis here is on the logistical and interconnecting support functions that allow the architecture to take on ambitious activities more effectively as the Artemis era unfolds.

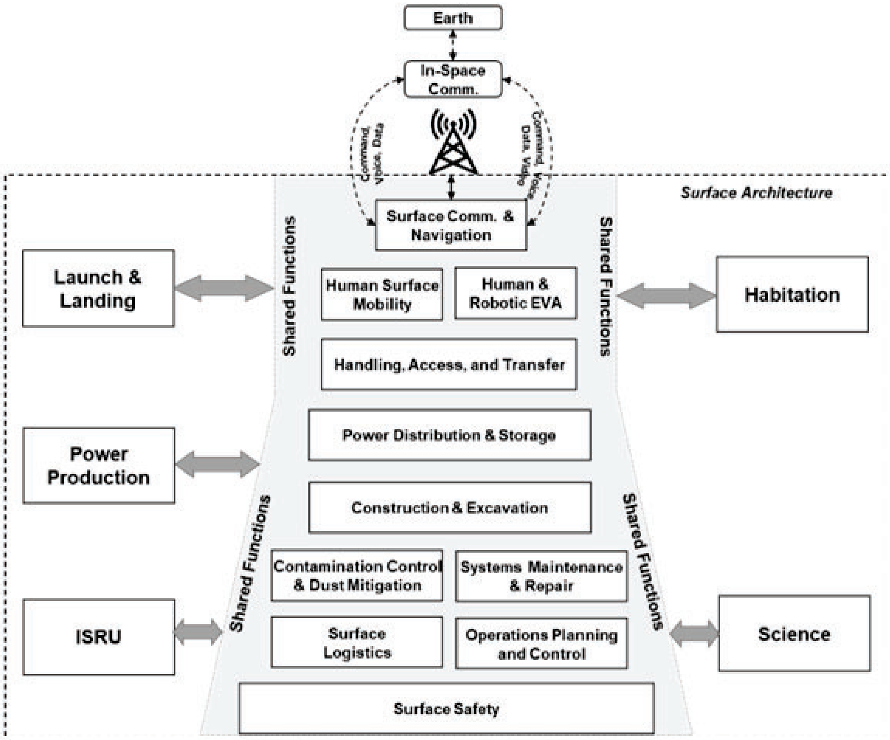


Figure 8.7-5. Notional Long-term Surface Operational Functions relevant to Workshop Objectives (This figure was a product for the NESC Workshop, by C. McCleskey and M. Lewis, KSC, June 8, 2022.)

Surface science operations during the Artemis era occur in a cycle of human-robotic activity, as depicted in Figure 8.7-6. Without humans, the surface is prepared, and systems are deployed as necessary via various uncrewed modes of operation. The surface is robotically explored, and unique science from the Moon (e.g., astrophysical observations) can occur in various uncrewed modes, with assistance from remote crews based either in space (i.e., Gateway) or from Earth. Given the short ~2-sec latency telerobotic operations from Earth and the need to prioritize astronaut time when they are at the Gateway, it is likely that telerobotic operation of robots on the lunar surface from Earth will be the more efficient approach.

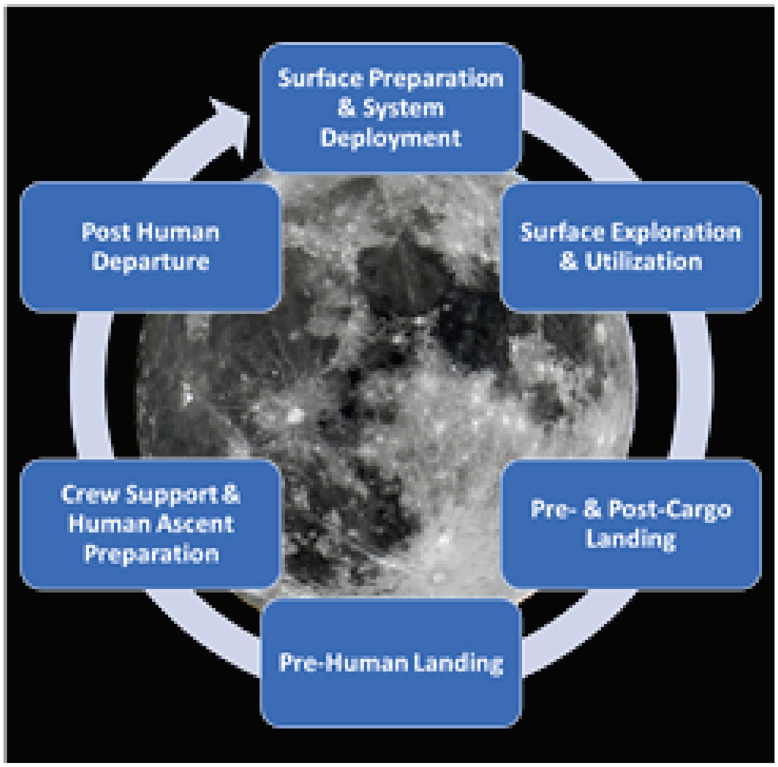


Figure 8.7-6. Cycle of Lunar Surface Activity with Shackleton Crater Emphasized

Certain systems can then prepare for the arrival of the human crews on the surface. Once the crew arrives, planned activities using the unique capabilities of the surface crew begin, and the unique abilities of surface-based machines can aid the expedition in its science activities.

Some of these may include science intravehicular activities (IVAs) inside pressurized volumes, or EVAs by suited surface crews. Additionally, extravehicular robotic (EVR) activities will combine the strengths of humans and machines on the lunar surface.

An example of a lunar science facility deployment objective was taken up by the workshop (i.e., emplacement of a radio telescope or, more ambitiously, a network of such instruments on the far side of the Moon (see Figure 8.7-7)). The surface operations and support functions shown in Figure 8.7-5 are all likely needed for this application in some manner.

Basic concepts of deployment have been proposed (e.g., Bandyopadhyay et al. [2021a] and Burns et al. [2019a]). However, these require further architectural exploration and engineering analysis (e.g., documented concepts of power, robotic design and development, delivery and logistics, risk analysis, cost analyses, etc.). These concepts may benefit from a combination of human and robotic activity, such as pre-arrival robotic setups/prefabricated deployments, assembly operations, and unforeseen nonconformances, which are better handled by on-site crews to ensure the success of the science and sustain the observatory operations.

Ahead of such ambitious undertakings are science site master planning and governance of science activities, in addition to the delivery, emplacement, construction, assembly, activation, test, operations, and sustainment tasks. Also, the cost and economics of the endeavor should be examined.

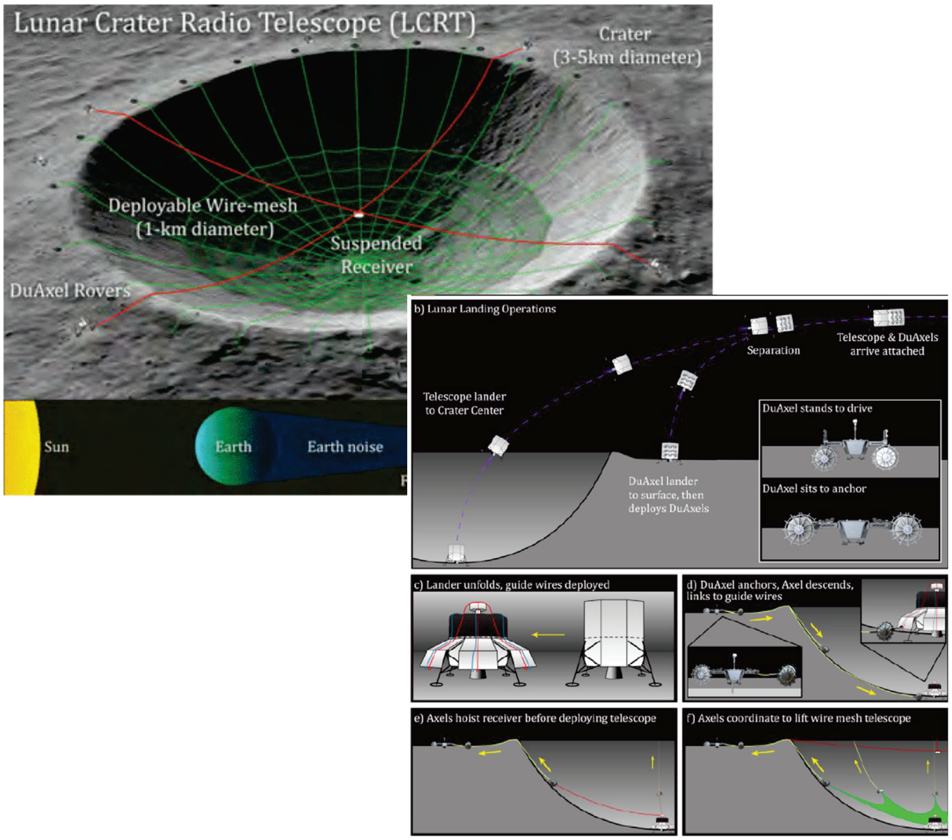


Figure 8.7-7. Concepts for Lunar Crater Radio Telescope (LCRT) on Far Side of Moon [reprinted with permission from S. Bandyopadhyay, JPL]

In summary, architectural trades are needed, with a view toward a long-term, comprehensive functional scope to determine best means to meet science facility deployment objectives across the science facility life cycle (see Figure 8.7-8).

Types of Surface Science Support

Infrastructure can grow to accommodate more science capabilities and services available to scientists. Examples include

- Power Supply to Surface Science Assets
- Human Support to Surface Science Crews
- IVA, EVA, EVR, Gateway, Earth-based
- Surface Mobility of Human Science Crews
- Science Information Support on the Surface
- Science Comm, Navigation, Pointing, Tracking
- Surface Science Imagery
- Contamination Control Support-Dust Mitigation
- Surface Safety Support for Science
- Engineering Support for Science Activity
- Science Logistics Support (spares, supply/disposal)
- Science Planning, Scheduling, Deconfliction
- Access Support to Science Subjects, Equipment, Sensors and Electronics
- Heavy Equipment Transfer Support Across Surface of Large Scientific Equipment, Assemblies and Materials/Commodities
- Construction Support of Science Stations
    - Excavation Services
    - Human/Robotic Assembly Services
- Other Support Services
    - Fabrication
    - Cleaning
    - Maintenance, Repair and Malfunction Analysis
    - Metrology / Calibration
    - Storage

Figure 8.7-8. Infrastructure for Lunar Surface Science

F-4. To avoid costly and potentially hazardous designs, systems engineering for both science payloads and exploration capabilities must bridge the HQ mission directorate stovepipes.

F-5. Currently, science requirements are being retrofitted to the Artemis capabilities, which is limiting the possibilities and unlikely to enable breakthrough decadal-level science.

8.8 International and Interagency Partnerships

8.8.1 International Collaborations

The PDS2023 noted that international participation in human programs has the benefit of (1) spreading the cost out over a larger number of participating entities and making it more affordable to each, (2) providing wider participation of scientists, engineers, and the public from different countries and cultures, and (3) enhancing international cooperation in peaceful endeavors.

The NESC workshop attendees heard that the European Space Agency (ESA) has commenced a Topical Team study of a low frequency radio array on the lunar far side that is similar to FARSIDE. Professor Marc Klein Wolt from Radboud University in the Netherlands leads this team in developing the concept for the Astronomical Lunar Observatory (ALO). The science goals for ALO are also similar to FARSIDE, with a focus on measuring the global 21-cm spectrum from the early star-forming epochs of the Universe. The proposed ALO would synergize with the ESA/US human lunar exploration program, while building on European technology heritage. ALO is one of several ESA concept studies currently underway, including a Polar Explorer mission and a Bioscience Moon mission that includes utilization of a European Moon Rover system. ALO would make use of the European Large Logistics Lander (Figure 8.8.1-1), which can deliver 1.5 metric tons to the surface, analogous to goals for NASA's next-generation CLPS landers. ALO would employ an ESA multi-purposed modular mobility solution for antenna deployment that can carry ~200 kg. In addition, ESA is designing power stations based on photovoltaics and possibly a mini-nuclear reactor to power activities such as the ALO. The timetable for potential operations on the Moon would be the mid-2030s. At present, the ALO Topical Team is focusing on defining the science objectives and requirements and coordinating the technology developments.

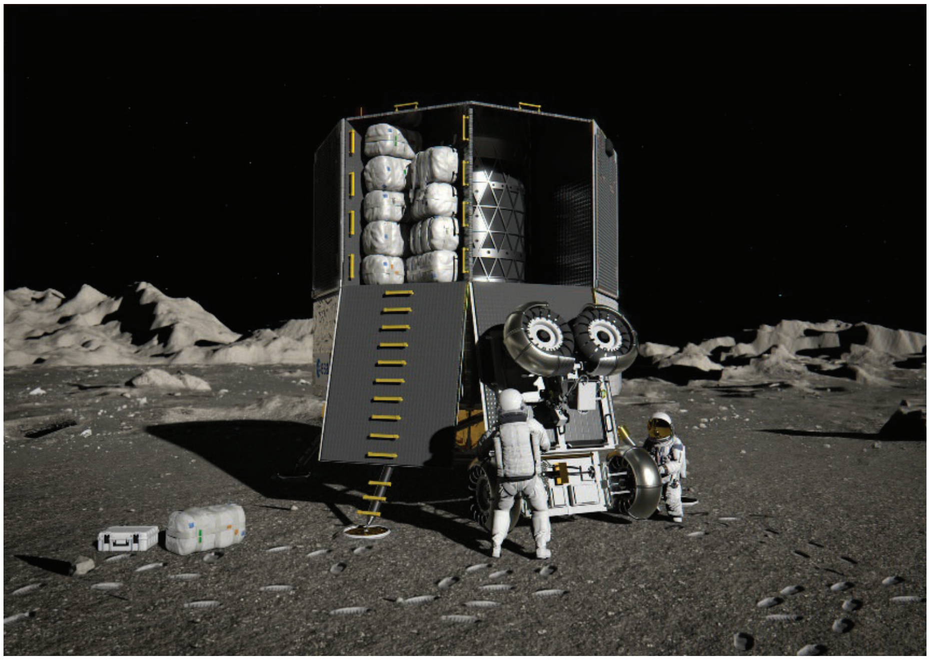


Figure 8.8.1-1. European Large Logistics Lander unloading Cargo on the Moon [Courtesy of ESA]

Given the similarities in scientific goals, engineering designs, deployment strategies, and lunar infrastructure requirements, there is an exciting opportunity for international collaboration on building a low frequency array on the lunar far side. There is substantial precedent for such international partnerships for astronomical observatories on the ground, including the Atacama Large Millimeter/submillimeter Array (ALMA) telescope in Chile and SKA radio telescopes. In the short term, it is recommended that NASA identify and collaborate on technology developments. In the longer term, NASA should work toward a common lunar array design and build the array from multiple launches by individual partners.

F-6. There is interest in Europe toward building a low-frequency radio telescope array on the lunar far side. Interagency partnering is to be encouraged.

8.8.2 Governmental Interagency Collaborations

Recently, NASA and the DOE negotiated a memorandum of understanding (MOU) for collaborations between the two agencies that includes lunar-based science[7].

LuSEE-Nite (PI Stuart Bale, UC-Berkeley; A. Slosar is DOE lead) is the first example of a funded partnership between NASA and DOE resulting from the MOU (see Section 6.5.5). LuSEE-Nite is a pathfinder radio telescope that is scheduled to land on the lunar far side in 2025. NASA provides the launch through the CLPS Program and DOE/NASA share funding on the radio instrument design and construction. For the first time, sufficient batteries will be carried to the Moon to allow operations at night to explore the wavelength window of 1 to 50+ MHz, which encompasses 21-cm neutral hydrogen radiation from the Dark Ages.

At the DOE, the physics of the Dark Ages is housed within the Office of High Energy Physics (HEP) that resides inside the Office of Science. HEP is divided into six research areas, including the Cosmic Frontier that addresses questions involving the early Universe—dark matter, dark energy, and cosmic inflation—all of which can potentially be probed via the 21-cm line generated from the Dark Ages. In general, the experiments selected by HEP for funding are driven by a bottoms-up community process known as Snowmass/P5. Snowmass is a series of workshops that result in community recommendations; P5 is the Particle Physics Project Prioritization Panel that issues a report on science priorities within different budget scenarios. NASA and DOE have had several successful shared-cost partnerships, including the Fermi-GLAST gamma-ray observatory and the AMS. LuSEE-Nite was created by a top-down NASA/DOE MOU and a community-sounding RFI. It was enabled by DOE's desire for more medium and small projects, by the opportunity for a CLPS-funded ride to the Moon's surface that was too good to miss, and the MOU providing an opportunity to request extra funding from Congress. However, future potential lunar high-energy science experiments will need to be recommended by the Snowmass/P5 process.

F-7. The 21-cm cosmology community needs to demonstrate to the DOE Office of HEP the importance of Dark Ages investigations as a priority for future Snowmass/P5 recommendations.

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[7] https://www.nasa.gov/press-release/nasa-department-of-energy-expand-on-more-than-50-years-of-collaboration

F-8. NASA, ESA, and DOE have overlapping science interests in using the lunar surface as a platform for radio astronomy and other science.

O-8. To avoid duplication of effort and maximize resources, joint NASA and DOE planning on the requirements to deliver, deploy, and service scientific payloads on the lunar surface should be pursued.

8.9 Proposed Artemis Mission Requirements for Sustained Scientific Exploration

The merging of science and human exploration presents a unique challenge compared with the typical manner in which robotic science missions are formulated, where the primary goal of the mission is purely science, the primary drivers for mission design are cost and the size of the launch vehicle, and the risk posture is less rigid. Human missions focus first and foremost on safely launching and returning crew, so science objectives often must fit into the “box” provided by the human mission architecture.

F-9. For Artemis IV and beyond, the science requirements need to be captured with an up-front Science Definition Team (SDT) process for both large strategic observatories and more modest “Explorer class” competed opportunities.

F-10. Delivery of scientific payloads to the lunar surface in the late 2020s and beyond may require larger down-mass and volumes than the current CLPS capabilities. Planning future requirements for CLPS 2.0 based on possible scientific investigations should begin now to prepare for future decadal surveys (i.e., Astro2030 and Planetary 2032).

Two examples of this include HST designed around shuttle capability and that ISS science was retrofitted into the program. The HST was designed specifically to utilize the space shuttle for deployment and servicing, as well as shuttle-based EVA for repairs or upgrades. HSTs size was specified to be packaged and carried to orbit in the shuttle’s payload bay, and HST was outfitted with a grapple-fixture capable of being captured by the space shuttle’s Canadarm for berthing in the cargo bay or deployment. The HST was outfitted with EVA-compatible handrails, latches, bolts, portable foot restraints, and orbitally replaceable internal experiments for EVA astronaut servicing. The ISS Program considered science and payloads from the outset; however, in 2014 the Program realized its processes for using the ISS as a laboratory and science platform were byzantine and not friendly to the community it wished to serve. It undertook an internal process and cultural transformation from “assembly” mode to a “science discovery/commercialization” mode with a Program called RISE, Revolutionize ISS for Science and Exploration, which has significantly increased the science utilization of the station since assembly complete configuration.

The Artemis architectural asset that provides lunar surface access is the HLS. At the time of writing this report, the HLS procurement path [NASA NextSTEP Appendix P, 2022] is transitioning from its “initial” phase (i.e., design studies, risk reduction activities, and initial development) to full development and demonstration. Future large-scale science investigations like the ones envisioned in this report will rely on the still to-be-defined recurring transportation services contract, transitioning from short-duration “sortie” missions to longer-duration “excursion” missions and the establishment of the ABC. All of these “design reference missions” define utilization requirements and baseline ConOps, including crew staging vehicle, surface crew size, surface mission duration, landing location, amount of lunar nighttime operations allowed, surface habitation element, number and duration of EVAs, and payload mass to/from the surface.

Other considerations relevant to surface science investigations include operations, mobility, power, communications, and servicing.

R-5. Beyond Artemis IV, the SMD and the ESDMD should continue to be empowered to collaboratively define mission requirements to accomplish decadal-level science via human exploration missions.

8.9.1 Operations

The primary function of surface science is the gathering of science data through a variety of types of instruments and sensors. The success of a lunar science mission depends on a properly designed and built space segment, a successful launch and lunar landing, the ground segment, and successful mission operations, carried out by a team of experts using the infrastructure and processes of the mission’s ground segment. The in-space operations for lunar science depends on two phases of equal importance: mission preparation and mission execution. The below sections describe considerations for the operations phase: mobility/transport, power, interfaces, communications/telemetry, and servicing/repair.

8.9.2 Mobility/Transport

All lunar surface science will need to be brought to the lunar surface on different varieties of landers. Some landers may be specifically designed to transport only science (i.e., the CLPS landers). Some science packages or elements/sensors will need to be deployed to or along the lunar surface, requiring deployment mechanisms, cranes/ramps, and or mobility systems. Deployment and mobility systems should attempt to be autonomous unless they are brough to the surface with astronaut crew EVA in their primary plan (e.g., systems delivered with HLS lunar landers).

8.9.3 Payload Power/Interfaces

Science experiments and sensor packages will require power to function. Longer-term power requirements for science may require solar power systems and batteries or radioisotope thermoelectric generators (RTGs). Science systems that are deployed near certain permanent lunar facilities could take advantage of distributed power systems, once available.

8.9.4 Communications Bandwidth and Noise Considerations

Science data are converted to telemetry and sent back to Earth through a proposed lunar communications network and the DSN. Most science experiments will require a forward command path for instruments; however, bandwidth restrictions, satellite coverage, and radio quiet regions will limit continuous communications. Science data and telemetry is routed to appropriate Payload Investigators and science teams through appropriate distribution networks and control centers.

F-11. With a short ~2-5 sec communication latency time, telerobotics operation from the Earth maybe be acceptable compared with control conducted by astronauts in cislunar space.

There may be a time efficiency and potential for 24-hour operations to be gained by Earth telerobotic operation compared with using very limited cislunar crew time. Such operations can be the precursor to lunar surface human-robotic operations.

8.9.5 Are Repeat Visits/Servicing Required?

If a science experiment or deployed payload requires astronaut EVA repair or servicing for upgrades, the appropriate EVA interfaces should be designed into the system for ease of access and replacement of components. Use of the appropriate NASA standards for handling, connectors, replaceable units, and sharp edges, as well as appropriate design reviews and consultations should be employed early in design. Science payloads should not require use of unique tools but should utilize the NASA standard for EVA tools and interfaces.

Another factor to consider is whether assets can be deployed (cargo delivery) or constructed robotically in advance of the human presence. Large-scale surface endeavors must consider the efficiency and interoperability of *in-situ* manufacturing versus robotic delivery versus human delivery. Science operations should be designed to be as autonomous as practical without EVA astronaut requirements for deployment.

9.0 Findings, Observations, and Recommendations

9.1 Findings

F-1. Realizing use of the Moon as a platform for science will require high-priority science and mission endorsements from future decadal surveys.

F-2. While the lunar surface environment is challenging, with dust contamination and maintaining a far-side radio quiet zone being the major concerns, no showstoppers to using the Moon as a platform for science observatories were identified.

F-3. The frequencies being observed by proposed low-frequency radio telescopes are lower than typically used for spacecraft communications, so the major concern with maintaining the SZM is with broadband radio emitters (i.e., high-power switching circuits, motors, and digital noise from computers).

F-4. To avoid costly and potentially hazardous designs, systems engineering for both science payloads and exploration capabilities must bridge the HQ mission directorate stovepipes.

F-5. Currently, science requirements are being retrofitted to the Artemis capabilities, which is limiting the possibilities and is unlikely to enable breakthrough decadal-level science.

F-6. There is interest in Europe toward building a low-frequency radio telescope array on the lunar far side. Interagency partnering is to be encouraged.

F-7. The 21-cm cosmology community needs to demonstrate to the DOE Office of HEP the importance of Dark Ages investigations as a priority for future Snowmass/P5 recommendations.

F-8. NASA, ESA, and DOE have overlapping science interests in using the lunar surface as a platform for radio astronomy and other science.

F-9. For Artemis IV and beyond, the science requirements need to be captured with an up-front Science Definition Team (SDT) process for both large strategic observatories and more modest "Explorer class" competed opportunities.

F-10. Delivery of scientific payloads to the lunar surface in the late 2020s and beyond may require larger down-mass and volumes than the current CLPS capabilities. Planning future requirements for CLPS 2.0 based on possible scientific investigations should begin now to prepare for future decadal surveys (i.e., Astro2030 and Planetary 2032).

F-11. With a short ~2-5 sec communication latency time, telerobotics operation from the Earth may be acceptable compared with control conducted by astronauts in cislunar space. There may be a time efficiency and potential for 24-hour operations to be gained by Earth telerobotic operation compared with using very limited cislunar crew time. Such operations can be the precursor to lunar surface human-robotic operations.

9.2 Observations

O-1. Exploration that does not include science as one of the primary objectives is a lost opportunity and likely to mean the exploration program is not sustainable.

O-2. While there have been notable successes (e.g., HST, ISS), the scientific community is wary of engaging human exploration capabilities because of past changes in destinations, shifting priorities, and delays.

O-3. Science investigations of decadal-level quality must be a critical part of a sustained lunar presence and preparation for future Mars missions.

O-4. Fully robotic missions to deliver scientific payloads to the lunar surface have been studied and are feasible.

O-5. In the near future, there will likely be increased cooperation between human and robotic exploration.

O-6. The workshop participants concurred with PDS2023 findings and recommendations regarding NASA's Organizational Structure for Incorporating Science into Human Exploration.

O-7. Any human assembly of scientific instruments or observatories on the lunar surface should focus on items that cannot be affordably and technically implemented by robots.

O-8. To avoid duplication of effort and maximize resources, joint NASA and DOE planning on the requirements to deliver, deploy, and service scientific payloads on the lunar surface should be pursued.

9.3 Workshop Recommendations

The following NESC recommendations are directed to SMD and ESDMD for consideration:

R-1. All future decadal surveys should request briefings from NASA on the current status of the Artemis architecture and the overall Moon to Mars strategy in a public forum so that viable mission concepts can be discussed and proposed.

R-2. Adequate low-frequency RFI testing, screening, and shielding must be considered for all spacecraft and payloads that will be visible from the lunar radio quiet zone. Spacecraft equipment destined for the SZM must be designed to standards to minimize RFI and be subjected to radio noise validation tests.

R-3. To enable servicing, design of future observatories or instruments deployed on the lunar surface should follow the HST and ISS models, where standards are followed to make them astronaut friendly for servicing (e.g., standard bolt sizes, easily accessible electronics cards, avoidance of sharp edges).

R-4. To ensure the safety of the crew on prolonged missions, early environmental testing should be conducted for life support system tolerances and hardware exposure impacts during initial Artemis missions.

R-5. Beyond Artemis IV, the SMD and the ESDMD should continue to be empowered to collaboratively define mission requirements to accomplish decadal-level science via human exploration missions.

10.0 Alternate Technical Opinion(s)

No alternate technical opinions were identified during the course of this assessment by the NESC assessment team or the NESC Review Board (NRB).]

11.0 Other Deliverables

No unique hardware, software, or data packages, other than those contained in this report, were disseminated to other parties outside this assessment.]

12.0 Recommendations for the NASA Lessons Learned Database

No recommendations for NASA lessons learned were identified as a result of this assessment.

13.0 Recommendations for NASA Standards, Specifications, Handbooks, and Procedures

No recommendations for NASA standards, specifications, or procedures were identified as a result of this assessment.

14.0 Definition of Terms

Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Lesson Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, such as a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which is not directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive

	acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides a detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation, descriptions of assumptions, exceptions, clarifications, and boundary conditions.

15.0 Acronyms and Nomenclature List

µm	micron (micrometer)
3GPP	3rd Generation Partnership Project
°C	degrees Celsius
ABC	Artemis Base Camp
AKR	Auroral Kilometric Radiation
ALMA	Atacama Large Millimeter/submillimeter Array (telescope, Chile)
ALO	Astronomical Lunar Observatory
AMS	Alpha Magnetic Spectrometer
APL	Applied Physics Laboratory
arcmin	arcminute
Astro2020	Decadal Survey on Astronomy and Astrophysics 2020
AU	astronomical unit, roughly the distance from Earth to the Sun (equal to 150 million kilometers or 93 million miles)
BPS	Biological and Physical Sciences
CCD	Charge-coupled Device
CLPS	Commercial Lunar Payload Services
CMB	Cosmic Microwave Background
CME	Coronal Mass Ejection
CMI	Cyclotron Maser Instability
ConOps	Concept of Operations
CPNT	Communications, Pointing, Navigation, and Timing
DAM	Decametric Radio Emission
DIM	Decimetric Radiation
DOE	Department of Energy
DSN	Deep Space Network
DSNE	Design Specification for Natural Environments
EESS	Earth Exploration-satellite Service
ELF	Elliptical Lunar Frozen [orbit]
EM	Electromagnetic
ENA	Energetic Neutral Atom
EoR	Epoch of Reionization
ESA	European Space Agency
ESD	Electrostatic Discharge

ESDMD	Exploration Systems Development Mission Directorate
EUV	Extreme Ultraviolet
EVA	Extravehicular Activity
EVR	Extravehicular Robotic
FAST	Five-hundred-meter Aperture Spherical Radio Telescope
FDTD	Finite Difference Time Domain
FWHM	Full Width at Half Maximum
Gbps	gigabits per second
GCR	Galactic Cosmic Radiation
GHz	gigahertz
GNSS	Global Navigation Satellite System
HEP	Office of High Energy Physics, DOE
HEPA	High Efficiency Particulate Air [filter]
HERA	Hydrogen Epoch of Reionization Array
HI	Neutral Hydrogen Line
HLS	Human Landing System
HSO	Heliophysics System Observatory
HST	Hubble Space Telescope
Hz	hertz
IAU	International Astronomical Union
ICD	Interface Control Document
ILOA	International Lunar Observatory Association
ILO-X	Up-looking camera sponsored by the ILOA and built by Canadensys Aerospace; Intuitive Machines CLPS mission 1 (IM-1)
IM-1	Intuitive Machines 1 (CLPS mission)
IR	Infrared
ISRU	In Situ Resource Utilization
ITU	International Telecommunication Union
ISS	International Space Station
IVA	Intravehicular Activity
JAXA	Japan Aerospace Exploration Agency
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
kHz	kilohertz
km	kilometer
kW	kilowatt
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCRT	Lunar Crater Radio Telescope
LEAG	Lunar Exploration Advisory Group
LEU	Low Enriched Uranium
LOFAR	Low-frequency Array
LSSW	Lunar Surface Science Workshop
LUT	Lunar-based Ultraviolet Telescope
m	meter
MAG	Maximum Absorbency Garment
MAXI	Monitor of All-sky X-ray Image (JAXA)

Mbps	megabits per second
MHz	megahertz
mm	millimeter
MMOD	Micrometeoroid and Orbital Debris
MO	Missions of Opportunity
MRE	Molten Regolith Electrolysis
MWA	Murchison Widefield Array
NAIC	NASA Innovative Advanced Concepts
NAS	National Academy of Sciences
NICER	Neutron Star Interior Composition ExploreR (X-ray telescope on the ISS)
NSF	National Science Foundation
NTC	Non-thermal Continuum (radiation)
OVRO-LWA	Owens Valley Radio Observatory Long Wavelength Array
pc	parsec
PDS2023	2023-2032 National Academy of Sciences Planetary Decadal Survey
PEM	Proton Exchange Membrane
PI	Principal Investigator
PSR	Permanently Shadowed Regions
RAS	Radio Astronomy Service
RDSS	Radiodetermination Satellite Service
RF	Radio Frequency
RFC	Regenerative Fuel Cell
RFI	Radio Frequency Interference
RISE	Revolutionize ISS for Science and Exploration
RNSS	Radionavigation Satellite Service
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generator
SCaN	Space Communications and Navigation
SCEM	Scientific Context for Exploration
SDT	Science Definition Team
sec	second
SEE	Single Event Effect
SEP	Solar Energetic Particle
SFCG	Space Frequency Coordination Group
SLS	Space Launch System
SKA	Square Kilometre Array
SMD	Science Mission Directorate
SOFC	Solid Oxide Fuel Cell
SRS	Space Research Service
STD	Standard
STM	Science Traceability Matrix
STMD	Space Technology Mission Directorate
SZM	Shielded Zone of the Moon
TB	terabyte
THz	terahertz
TRL	Technology Readiness Level

TT&C	Telemetry, Tracking, and Control
UV	Ultraviolet
W/m^2	watts per square meter, solar irradiance

16.0 References

Abel, T., Bryan, G. L., and Norman, M. L., 2002. “The Formation of the First Star in the Universe,” *Science*, Vol. 295, Issue 5552, November 15, 2001, pp. 93-98.

Alexander, J. K., Kaiser, M. L., Novaco, J. C., Grena, F. R., and Weber, R. R. (1975). “Scientific Istrumentation of the Radio-Astronomy-Explorer-2 Satellite,” *Astronomy and Astrophysics*, Vol. 40, No. 4, May 1975, p. 365-371.

Anderson, M. M., Hallinan, G., Eastwood, M. W., Monroe, R. M., Vedantham, H. K., Bourke, S., Greenhill, L. J., Kocz, J., Lazio, T. J. W., Price, D. C., Schinzel, F. K., Wang, Y., and Woody, D. (2018). “A Simultaneous Search for Prompt Radio Emission Associated with the Short GRB 170112A Using the All-sky Imaging Capability of the OVRO-LWA”, The Astrophysical Journal, Vol. 864, Issue 1, article 22, September 2018.

Ansari, R., Arena, E. J., Bandura, K., Bull, P., Castorina, E., Chang, T.-C., Chen, S.-F., Connor, L., Foreman, S., et al. (2018). “Cosmic Visions Dark Energy: Inflation and Early Dark Energy with a Stage II Hydrogen Intensity Mapping Experiment,” Cosmic Visions 21-cm Collaboration, October 22, 2018. URL: https://doi.org/10.48550/arXiv.1810.09572

Artemis III Science Definition Team Report (2020). “Artemis III Science Definition Team Report,” NASA/SP-20205009602, December 4, 2020. URL: https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf

Artemis Plan (2020). “Artemis Plan—NASA’s Lunar Exploration Program Overview,” National Aeronautics and Space Administration, Washington, D.C., September 2020. URL: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan- 20200921.pdf

Arya, M., Verniani, A., Delapierre, M., Pisanti, D., Gupta, G., Goel, A., Lazio, J., Goldsmith, P., and Bandyopadhyay, S. (2023). “Kilometer-Scale Parabolic Reflector for a Radio Telescope in a Lunar Crater,” *AIAA SciTech Spacecraft Structures*, January 2023, submitted.

Ashtijou, M., Yang-Scharlotta, J., Hanelli, A., Han, M., Saebi, A., Del Castillo, L., Mojarradi, M., Norton, W. E., Wang, Z., and Blalock, B. (2020). “Select Electronic Parts Operation at Extreme Low Temperature,” 2020 IEEE Conference on Aerospace, Big Sky, Montana, March 7-14, 2020.

Bandyopadhyay, S., McGarey, P., Goel, A., Rafizadeh, R., Delapierre, M., Arya, M., Lazio, J., Goldsmith, P., Chahat, N., Stoica, A., Quadrelli, M., Nesnas, I., Jenks, K., and Hallinan, G. (2021a). “Conceptual Design of the Lunar Crater Radio Telescope (LCRT) on the Far Side of the Moon,” 2021 IEEE Conference on Aerospace, Big Sky, Montana, March 6-13, 2021. URL: http://publish.illinois.edu/saptarshibandyopadhyay/files/2021/02/LCRT_IEEE_Aerospace_2021.pdf

Bandyopadhyay, S., Lazio, J., Goldsmith, P., McGarey, P., Goel, A., Rafizadeh, R., Delapierre, M., Arya, M., Chahat, N., Stoica, A., Quadrelli, M., Nesnas, I., Jenks, K., Hallinan, G., and

Wilson, R. (2021b). “Lunar Crater Radio Telescope (LCRT) on the Far Side of the Moon,” Technical Report NASA Innovative Advanced Concepts (NIAC) Phase 1 Report, 2021.

Bassett, N., Rapetti, D., Burns, J. O., Tauscher, K., and MacDowall, R. (2020). “Characterizing the Radio Quiet Region behind the Lunar Farside for Low Radio Frequency Experiments,” *Advances in Space Research*, Vol. 66, Issue 6, September 15. 2020, pp. 1265-1275.

Bastian, T. S., Dulk, G. A., and Leblanc, Y. (2000). “A Search for Radio Emission from Extrasolar Planets,” *The Astrophysical Journal*, Vol. 545, Issue 2, December 2000, pp. 1058-1063.

Bolton, S., Levin, S., Gulkis, S., Klein, M., Sault, R., Bhattacharya, B., Thorne, R., Dulk, G., and Leblanc, Y. (2001). “Divine-Garrett Model and Jovian Synchrontron Emission,” *Geophys. Res. Letts*., Vol. 28, Issue 5, March 1, 2001, p. 907.

Book, L., Kamionkowski, M., and Schmidt, F. (2012). “Lensing of 21-cm Fluctuations by Primordial Gravitational Waves,” *Phys. Rev. Lett.*, Vol. 108, 211301, May 25, 2012. DOI: 10.1103/PhysRevLett.108.211301

Buhler, C. R., Calle, C. I., Clements, S. J., Mantovani, J., and Ritz, M. I. (2007). “In Situ Test Method for the Electrostatic Characterization of Lunar Dust,” 2007 IEEE Aerospace Conference, Big Sky, MT, March 3-10, 2007.

Burns, J. O. , Hallinan, G., Lux, J., Teitelbaum, L. et al. (2019a). “Probe Study Report: FARSIDE (Farside Array for Radio Science Investigations of the Dark ages and Exoplanets),” NASA, November 2019. URL: https://science.nasa.gov/science-pink/s3fs-public/atoms/files/FARSIDE_FinalRpt-2019-Nov8.pdf

Burns, J. O., Mellinkoff, B., Spydell, M., Fong, T., Kring, D. A., Pratt, W. D., Cichan, T., and Edwards, C. M. (2019b). “Science on the Lunar Surface Facilitated by Low Latency Telerobotics from a Lunar Orbital Platform – Gateway,” *Acta Astronautica*, Vol. 154, January 2019, pp. 195-203.

Burns, J. O., MacDowall, R., Bale, S., Hallinan, G., Bassett, N., and Hegedus, A. (2021). “Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions,” *The Planetary Science Journal*, Vol. 2, No. 2, March 8, 2021, p. 44.

Calvert, W. (1987). “Hollowness of the Observed Auroral Kilometric Radiation Pattern,” *J. Geophys. Res*., Vol. 92, Issue A2, February 1, 1987, pp. 1267-1270.

Carruthers, G. (1973). “Apollo 16 Far-Ultraviolet Camera/Spectrograph: Instrument and Operations,” *Applied Optics*, Vol. 12, Issue 10, 1973, pp. 2501-2508. URL: https://opg.optica.org/ao/fulltext.cfm?uri=ao-12-10-2501&id=18136

Chen, X., Burns, J. O., Koopmans, L., et al. (2019). “Discovering the Sky at the Longest Wavelengths with Small Satellite Constellations,” ISSI-BJ Forum, January 23-25, 2019, Beijing, China, January 23, 2019. URL: https://arxiv.org/abs/1907.10853

Clancey, W. J. (2006). “Clear Speaking About Machines: People are Exploring Mars, Not Robots,” Association for the Advancement of Artificial Intelligence Workshop: The Human Implications of Human-Robotic Interaction, January 2006.

Clark, S. J., Dutta, B., Gao, Y., Ma, Y.-Z. and Strigari, L. E. (2018). "21-cm Limits on Decaying Dark Matter and Primordial Black Holes," *Phys. Rev. D*, Vol. 98, Issue 4, 043006, August 15, 2018.

Elphic, R. C., et al. (2015). "Annual Meeting of the Lunar Exploration Analysis Group (LEAG)," October 20-22, 2015, Columbia, Maryland, LPI Contribution No. 1863, p. 2083.

Free, J. and Vogel, K. (2022). "Moon to Mars Strategy Briefing; National Aeronautics and Space Administration," Washington, D.C., May 16, 2022.

Gaier, J. R. (2005). "The Effects of Lunar Dust on EVA Systems During the Apollo Missions," NASA/TM—2005-213610, March 1, 2005. URL: https://ntrs.nasa.gov/citations/20050160460

Gaier, J. R., Siamidis, J., and Larkin, E. M. G. (2010). "Effect of Simulated Lunar Dust on the Properties of Thermal Control Surfaces," *Journal of Spacecraft and Rockets*, Vol. 47, No. 1, January 2010, pp. 147–152.

Gaier, J. R., Hicks, M. C., and Misconin, R. M. (2013). "Studies of Simulated Lunar Dust on the Properties of Thermal-Control Surfaces," *Journal of Spacecraft and Rockets,* Vol. 50, No. 4, July 2013, pp. 848–852.

Gainor, C. (2021). "Not Yet Imagined: A Study of the Hubble Space Telescope," January 6, 2021, pp. 249-250. URL: https://www.nasa.gov/connect/ebooks/not-yet-imagined.html

Green, J. L. (1984). "The Io Decametric Emission Cone," *Radio Sci.*, Vol. 19, No. 2, March/April 1984, pp. 556-570.

Green, J. L. and Boardsen, S. A. (2006). "Kilometric Continuum Radiation," *The Radio Science Bulletin*, No. 318, September 2006, pp. 34-41.

Green, J. L., Draper, D., Boardsen, S., and Dong, C. (2020). "When the Moon had a Magnetosphere," *Sci. Adv.*, Vol. 6, No. 42, October 14, 2020. DOI: 10.1126/sciadv.abc0865

Green, J. L. and Gallagher, D. L. (1985). The Detailed Intensity Distribution of the AKR Emission Cone," *J. Geophys. Res.*, Vol. 90, No. A10, October 1, 1985, pp. 9641-9649.

Gupta, G., Arya, M., Goel, A., Bandyopadhyay, S., Goldsmith, P., Mcgarey, P., Lazio, J., and Chahat, N. (2022). "Detector Development for the Lunar Crater Radio Telescope," 2022 IEEE Wireless Antenna and Microwave Symposium (WAMS), Rourkela, India, June 5-8, 2022.

Hill, J. G. and Baxter, E. J. (2018). "Can Early Dark Energy Explain EDGES?" *J. Cosmology Astropart. Phys*., Volume 2018, No. 8 (August), August 24, 2018.

HLS-UG-001 (2021). Human Landing System Lunar Thermal Analysis Guidebook, HLS-UG-001 Baseline, 1/4/2021. URL: https://ntrs.nasa.gov/citations/20210010030.

Horanyi, M., Szalay, J. R., Kempf, S., Schmidt, J., Grun, E., Srama, R., and Sternovsky, Z. (2016). "A Permanent, Asymmetric Dust Cloud around the Moon," *Nature*, Vol. 522, June 17, 2015, pp. 324-326.

International Agency Working Group (2016). "Dust Mitigation Gap Assessment Report," International Space Exploration Coordination Group (ISECG) Gap Assessment Team, February 9, 2016. URL: https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

Kaczmarzyk, M., Gawronski, M., and Piatkowski, G. (2018). “Global Database of Direct Solar Radiation at the Moon’s Surface for Lunar Engineering Purposes,” *E3S Web Conference*, Vol. 49, Article No. 00053, August 13, 2018.

Kocz, J., Greenhill, L. J., Barsdell, B. R., and Bernardi, G. (2014). “A Scalable Hybrid FPGA/GPU FX Correlator,” *J. Astron. Instrumentation*, Vol. 3, No. 1, January 2014. DOI: 10.1142/S2251171714500020.

Kramer, G. Y., Kring, D. A., Nahm, A. L., and Pieters, C. M. (2013). “Spectral and Photogeologic Mapping of Schrodinger Basin and Implications for Post-South Pole-Aitken Impact Deep Subsurface Stratigraphy,” *Icarus*, Vol. 223, March 1, 2013, p. 131-148.

Lewis, A., and Challinor, A. (2007). “21-cm Angular-Power Spectrum from the Dark Ages,” *Physical Review D*, Vol. 76, 083005, 2007.

Loeb, A., and Furlanetto, S. R. (2013). *The First Galaxies in the Universe*, Princeton Series in Astrophysics, Princeton University Press, Januaryt 15, 2013.

Lunar and Planetary Institute (2022). “Artemis III Science Definition Team White Papers,” URL: https://www.lpi.usra.edu/announcements/artemis/whitepapers/

Lunar Exploration Analysis Group (2016). The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities,” URL: https://www.lpi.usra.edu/leag/LER-2016.pdf

Lunar Exploration Analysis Group (LEAG) (2018). “Advancing Science of the Moon: Report of the LEAG Specific Action Team,” URL: https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

Mao, Y., Tegmark, M., McQuinn, M., Zaldarriaga, M., and Zahn. O. (2008). “How Accurately can 21cm Tomography Constrain Cosmology?” Phys. Rev. D, Vol. 78, 023529, July 25, 2008. URL: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.78.023529

McKay, D. S., Heiken, G., Basu, A., Blanford, G., Simon, S., Reedy, R., French, B. M., Papike, J. (1991). “Chapter 7: The Lunar Regolith,” *Lunar Sourcebook, A User’s Guide to the Moon*, (Heiken, G. H., Vaniman, D. T., and French, B. M., authors), Cambridge University Press, 1991. URL: https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter07.pdf

Meier, R. R. (1991). “Ultraviolet Spectroscopy and Remote Sensing Of The Upper Atmosphere,” *Space Science Reviews*, Volume 58, Issue 1, 1991, pp.1-185.

Muñoz, J. B. and Loeb, A. (2018). “A Small Amount of Mini-Charged Dark Matter could Cool the Baryons in the Early Universe,” *Nature,* Vol. 557, May 30, 2018, pp. 684-686.

Muñoz, J. B., Ali-Haïmoud, Y., and Kamionkowski, M. (2015). “Primordial Non-Gaussianity from the Bispectrum of 21-cm Fluctuations in the Dark Ages,” *Physical Review* D, Vol. 92, 083508, October 5, 2015.

Murphy, T. W., Adelberger, E. G., Battat, J. B. R., Hoyle, C. D., McMillan, R. J., Michelsen, E. L., Samad, R., Stubbs, C. W., and Swanson, H. E. (2010). “Long-Term Degradation of Optical Devices on the Moon,” *Icarus*, Vol. 208, March 3, 2010, pp. 31-35.

NASA BIG Idea Challenge Press Release (2021). “NASA Selects University Teams to Develop Ways to Deal with Moon Dust, NASA’s BIG Idea Challenge,” press release, January 29, 2021.

See NASA Selects University Teams to Develop Ways to Deal with Moon Dust | NASA; and NASA SBIR Phase I Solicitation, January 2022, URL: https://sbir.nasa.gov/print/79741

NASA Dust Mitigation Best Practices Guide, to be published.

NASA NextSTEP Appendix P (2022). "NextSTEP Appendix P: Human Landing System Sustaining Lunar Development," Solicitation number NNM19ZCQ001K_Appendix-P-SLD. URL: https://www.nasa.gov/nextstep/humanlander4

NASA-STD-1008 (2021). "Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments," baseline version, September 21, 2021. URL: https://standards.nasa.gov/standard/nasa/nasa-std-1008

National Research Council (2007). "The Scientific Context for Exploration of the Moon," The National Academies Press, Washington, DC. URL: https://doi.org/10.17226/11954

National Research Council (2011). "Vision and Voyages for Planetary Science in the Decade 2013– 2022," The National Academies Press, Washington, DC. URL: https://solarsystem.nasa.gov/resources/598/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022

Paige, D. A. and Siegler, M. A. (2016). "New Constraints on Lunar Heat Flow Rates from LRO DIVINER Lunar Radiometer Experiment Polar Observations," *Proceedings of the 47th Lunar and Planetary Science Conference*, Abstract No. 2753. URL: https://www.hou.usra.edu/meetings/lpsc2016/pdf/2753.pdf

PDS2023 (2022). "2023-2032 National Academy of Sciences Planetary Decadal Survey (PDS2023)." URL: Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 |The National Academies Press, last accessed September 12, 2022.

Slatyer, T. R. (2013). "Energy Injection and Absorption in the Cosmic Dark Ages," *Phys. Rev. D*, Vol. 87, 123513, June 14, 2013.

SLS-SPEC-159 (2021). "Cross-Program Design Specification for Natural Environments (DSNE)," SLS-SPEC-159, Rev. H, October 27, 2021. URL: https://ntrs.nasa.gov/citations/20205007447

STMD (2022). "LIVE: Thermal Management Systems," NASA Space Technology Mission Directorate, May 2022. URL: https://techport.nasa.gov/file/143283

Su, S.-Y., Yeh, H. C., and Heelis, R. A. (2001). "ROCSAT 1 Ionospheric Plasma and Electrodynamics Instrument Observations of Equatorial Spread F: An Early Transitional Scale Result," *Journal of Geophysical Research, Space Physics*, Vol. 106, Issue A12, December 1, 2001, pp. 29153-29159.

Takahashi, Y. D. (2003). New Astronomy from the Moon: A Lunar Based Very Low Frequency Radio Array," Master's Thesis, University of Glasgow, United Kingdom.

The Artemis III Science Definition Team (2020). "The NASA Artemis III Science Definition Team Report." URL: https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf

Wang, R., Gehlot, V., Bandyopadhyay, S., Goel, A., Byron, B., McGarey, P., Wilson, R., and Jenks, K. (2023). "Lift Wire Deployment and Anchoring System for the Lunar Crater Radio

Telescope on the Far Side of the Moon," *AIAA SciTech Space Exploration*, January 2023, submitted.

Wang, J., Meng, X. M., Han, X. H., Cai, H. B., Cao, L., Deng, J. S., Qiu, Y. L., Wang, S., Wei, J. Y., and Hu, J. Y. (2015). "18-Months Operation of Lunar-based Ultraviolet Telescope: a Highly Stable Photometric Performance," *Astrophys Space Sci*, Vol. 360, Article 10, October 7, 2015. URL: 18-Months operation of Lunar-based Ultraviolet Telescope: a highly stable photometric performance | SpringerLink

Wang, L., Germaschewski, K., Hakim, A., Dong, C., Raeder, J., and Bhattacharjee, A. (2018). "Electron Physics in 3D Two-Fluid Ten-Moment Modeling of Ganymede's Magnetosphere," *J. Geophys. Res. Space Physics*, Vol. 123, pp. 2815-2830. DOI:10.1002/2017JA024761.

Williams, J. P., Greenhagen, B. T., Paige, D. A., Schorghofer, N., Sefton-Nash, E., Hayne, P. O., and Aye, K. M. (2019). "Seasonal Polar Temperatures on the Moon," *Journal of Geophysical Research: Planets*, Vol. 124, No. 10, pp. 2505-2521.

Williams, J.-P., Paige, D. A., Greenhagen, B. T., Sefton-Nash, E. (2017). The Global Surface Temperatures of the Moon as measured by the Diviner Lunar Radiometer Experiment," *Icarus*, Volume 283, 2017.

Zarka, P. (2007). "Plasma Interactions of Exoplanets with their Parent Star and Associated Radio Emissions," *Planetary and Space Science*, Vol. 55, No. 5, pp. 598-617.

Zarka, P., Treumann, R. A., Ryabov, B. P., and Ryabov, V. B. (2001). "Magnetically-driven Planetary Radio Emissions and Application to Extrasolar Planets," *Astrophys. Space Sci.*, Vol. 277, pp. 293.

16.1 Additional References

Alibay, F., Lazio, T. J. W., Kasper, J. C., and Neilsen, T. (2017). "Sun Radio Interferometer Space Experiment (Sunrise) Proposal: Status Update," In AIAA/USU Conference on Small Satellites, Logan, UT, June 23, 2017.

Bandyopadhyay, S., Lazio, J., Stoica, A., Goldsmith, P., Blair, B., Quadrelli, M., de la Croix, J.-P., and Rahmani, A. (2018). "Conceptual Ideas for Radio Telescope on the Far Side of the Moon," In 2018 IEEE Aerospace Conference, March 3-10, 2018, pp. 1–10. DOI: 10.1109/AERO.2018.8396801

Bassett, N., Rapetti, D., Burns, J. O., Tauscher, K., and MacDowall, R. (2020). "Characterizing the Radio Quiet Region Behind the Lunar Farside for Low Radio Frequency Experiments," *Advances in Space Research*, Vol. 66, No. 6, September 15, 2020.

Datta, A., Bradley, R., Burns, J. O., Harker, G., Komjathy, A., and Lazio, T. J. W. (2016). "The Effects of the Ionosphere on Ground-Based Detection of the Global 21 cm Signal from the Cosmic Dawn and the Dark Ages," *The Astrophysical Journal*, Vol. 831, No. 1, pp. 6.

Furlanetto, S. R., Oh, S. P., and Briggs, F. H. (2006). "Cosmology at Low Frequencies: The 21cm Transition and the High-Redshift Universe, *Physics Reports*, Vol. 433, No. 4, pp. 181–301.

Furlanetto, S., Bowman, J. D., Mirocha, J., Pober, J. C., Burns, J., Carilli, C. L., Munoz, J., Aguirre, J., Ali-Haimoud, Y., Alvarez, M., Beardsley, A., Becker, G., Breysse, P., Bromm, V., Bull, P., Chang, T.-C., Chen, X., Chiang, H., Cohn, J., Davies, F., DeBoer, D., Dillon, J., Dor´e, O., Dvorkin, C., Fialkov, A., Hazelton, B., Jacobs, D., Karkare, K., Kohn, S., Koopmans, L., Kovetz, E., Plante, P. L., Lidz, A., Liu, A., Ma, Y.-Z., Mao, Y., Masui, K., Mesinger, A., Murray, S., Parsons, A., Saliwanchik, B., Sievers, J., Thyagarajan, N., Trac, H., Visbal, E., and Zaldarriaga, M. (2019). "Fundamental Cosmology in the Dark Ages with 21-cm Line Fluctuations," Astro 2020 Science White Paper, March 14, 2019. URL: https://arxiv.org/pdf/1903.06212.pdf

Gopalswamy, N. (2004). "Recent Advances in the Long-Wavelength Radio Physics of the Sun," *Planetary and Space Science*, Vol. 52, No. 15, pp. 1399–1413.

Rapetti, D., Tauscher, K., Mirocha, J., and Burns, J. O. (2020). "Global 21-cm Signal Extraction from Foreground and Instrumental Effects: ii. Efficient and Self-Consistent Technique for constraining Nonlinear Signal Models," *The Astrophysical Journal*, Vol. 897, No. 2, pp. 174.

Shen, E., Anstey, D., de Lera Acedo, E., Fialkov, A., and Handley, W. (2021). "Quantifying Ionospheric Effects on Global 21-cm Observations," *Monthly Notices of the Royal Astronomical Society*, Vol. 503, No. 1, May 2021, pp. 344–353.

Appendix A. Workshop Attendees

Attendee	Affiliation/Company Name
Laurie Abadie	GRC/Human Research Program (HRP)
Krystal Acosta	KSC
Brandon Aguiar	Florida International University
Caitlin Ahrens	GSFC/NPP
Machel Allen	N/A
Elyse Allender	Australian Space Agency
Timothy Anderson	NASA
Will Anderson	Intern
Tanya Andrews	MSFC
Lorella Angelini	GSFC
Samuelson Atiba	Cardiff University
Charmine Baboolal	East2
Amisha Baiju	Indian Institute of Science Education and Research Tirupati
Stuart Bale	University of California, Berkeley
Saptarshi Bandyopadhyay	JPL
Maria Banks	GSFC
Donald Barker	JSC/Jacobs
Jessica Barnes	University of Arizona
Tim Barrett	GSFC
Meghan Bartels	Space.com
James (Gerbs) Bauer	University of Maryland
Aleksey Bayborodin	TuyrX Civilian Space Project, TuyrX.com
Tracy Becker	Southwest Research Institute
Bill Beckman	The Boeing Company
Bryant Beeler	FiveBeeTechnologies
Margarita Belali	National Observatory of Athens
Mary Sue Bell	JSC/Jacobs, ARES
Esther Beltran	University of Central Florida
Mehdi Benna	GSFC
Loredana Bessone	ESA
Nathan Bickus	Lockheed Martin Space
Robert Biggs	Lockheed Martin
Jacquelyne Black	JSC
Eva Blaisdell	
Brad Blair	MoonRise, Inc.
Jacob Bleacher	GSFC
Sarah Boazman	ESA/ESTEC
Jay Bookbinder	ARC
Nicolò Boschetti	Johns Hopkins University (JHU)
Claude Boullevraye de Passillé	Deep Space Ecology, LLC
Lynn Bowman	LaRC
Tabetha Boyajian	Louisiana State University

Attendee	Affiliation/Company Name
Aaron Boyd	Arizona State University
Timothy Brady	JSC/NESC
Breana Branham	Lockheed Martin
Brian Breslin	
Chris Broadaway	KSC/NESC
Charles Buhler	KSC
Ethan Burbridge	GSFC
Jack Burns	University of Colorado, Boulder
Louis Burtz	LunarVision
Benjamin Byron	JPL/California Institute of Technology
Kathryn Bywaters	HoneyBee Robotics
John Callas	JPL
Lemuel Carpenter	LaRC
Andrea Casini	German Aerospace Center (DLR)
Abhishek Cauligi	JPL
Wesley Chambers	MSFC
Laura Champion	Lockheed Martin
Perry Channegowda	Raytheon Technologies Research Center
Ike Chi	JPL
Peter Chi	UCLA
Michael Ching	HQ/STMD
Chullhee Cho	Cryogenics and Fluids
A. Egon Cholakian	Harvard University/NIH/Oxford University
Sang-Hyon Chu	LaRC
Soyounh Chung	Korea Aerospace Research Institute
Ilaria Cinelli	AIKO
Christopher Cokinos	University of Arizona
Thomas Colvin	NASA Office of Technology, Policy, and Strategy
Douglas Cooke	Cooke Concepts and Solutions
John Cooper	GSFC Emeritus
Lourdes Cotto	KSC
Caroline Coward	JPL
Andrew Curtis	Oceaneering Space Systems
Shreyansh Daftry	JPL
William Danchi	GSFC
Ashwati Das-Stuart	JPL
Sarah Deitrick	Jacobs/JSC
Pablo DeLeon	University of North Dakota, Space Studies
Matthew Derosier	Raytheon
Anthony DeStefano	MSFC
Charles Dischinger	MSFC
Kyle Dixon	KSC
Sheperd Doeleman	Smithsonian Astrophysical Observatory
Janna Domenico	JHU Applied Physics Laboratory (APL)
Michelle Donegan	JHU APL
Adrienne Dove	University of Central Florida

Attendee	Affiliation/Company Name
Julie Edwards	University of Michigan
Ryan Edwards	GRC
Eisenman, David	JPL
Mark Elowitz	Network for Life Detection (NfoLD)
Michael Elsperman	The Boeing Company
Dean Eppler	The Aerospace Corporation
Chris Esser	Cairn Engineering, LLC
Marshall Eubanks	Space Initiatives Inv
Cynthia Evans	NASA
Loretta Falcone	ARC/KBR Wyle
Jay Falker	GSFC
Joseph Fillion	Jacobs
Michael Fiske	Jacobs Space Exploration Group
Nicholas Florio	Lockheed Martin Space
Bernard Foing	LUNEX/ILEWG EuroMoonMars Earth Space Innovation
Terry Fong	ARC
Christopher Forney	NE-L6
Denise Freeland	KSC
Ralph Fritsche	KSC
Carol Galica	HQ/Stellar Solutions, STMD LSII
Humberto García Montano	Observatorio Astronómico UNAN-Managua
Jessica Gaskin	MSFC
Carl Gelderloos	Universite of Colorado, Boulder, LASP
Thomas Giguere	University of Hawaii, HIGP
Ashish Goel	JPL
Marianne Gonzalez	JPL
Yvette Gonzalez	International Institute for Astronautical Sciences
Ryan Gott	KSC/UB-E
James Green	HQ
John Gruener	JSC
Carol Grunsfeld	N/A
John Grunsfeld	NASA Emeritus
Sunny Gupta	IISER Bhopal
Ugur Guven	UN CSSTEAP
Adrian Guzman	Mexican Space Agency
Jon Haas	WSTF/NESC
Inseob Hahn	JPL
Gregg Hallinan	Caltech
Christopher Hamilton	University of Arizona
Chuck Hammock	Andrews, Hammock & Powell, Inc.
Christy Hansen	NASA HQ
John Hanson	NASA Office of the Chief Engineer
Heather Hare	University of Michigan
Kate Harper	University of West Florida
Brian Harvey	BA & Associates

Attendee	Affiliation/Company Name
Sarah Hasnain	
Zachary Hassman	Oshkosh Corporation
David Hatfield,	Teledyne Brown Engineering, Inc.
Hava, Heather	Redwire/Deep Space Systems
Heidi Haviland	MSFC
Dan Hawk	United First Nations Planetary Defense
Jennifer Heldmann	ARC
Christine Hellweg	German Aerospace Center, Institute of Aerospace Medicine
Stefanie Hempel	WWU Münster
Allison Hercules	KLXS-III
Mike Hess	JSC
Tilak Hewagama	GSFC
Bradley Hill	GSFC
Timothy Hill	MSFC
Benjamin Hockman	JPL/California Institute of Technology
Robert Hoffmeister	Goodly Innovations
Amanda Honer	GRC/NESC
Samuel Howard	GRC
Ian Howley	MSFC
Michelle Hui	MSFC
John Huleis	JPL
Jose Hurtado	UTEP
Indermuehle Balthasar	CSIRO
Islam Kazi	
Jain Rashi	Purdue University
Ian Jakupca	GRC
Karan Jani	Vanderbilt University
Susan Jansen	GRC
Devanshu Jha	
Kathleen John	With Kristen John
Kristen John	JSC/STMD
Greg Johnson	Swedish Space Corporation
Jourdan Johnson	Northeastern University
Taylor Johnson	
Jennifer Jones	MSFC/ESSCA
Gyula Jozsa	Max-Planck-Institut für Radioastronomie
Gwang Ju	KARI
Fred Jue	Aerojet Rocketdyne
Insoo Jun	JPL
Sylvester Kaczmarek	WeSpace
Kagey, Jaclyn	JSC, FOD EVA
John Karcz	ARC
Kased, Nora	Jen-K USA
stavros katsanevas	European Gravitational Observatory
Joel Kearns	HQ

Attendee	Affiliation/Company Name
BeBe Kelly-Serrato	Paragon Space Development Corporation
Logan Kennedy	
Eddie Khan	Awake Aerospace
Michael Khayat	JSC, Wireless and Communication Systems
Richard Kidd	JPL
Eunhyeuk Kim	Korea Aerospace Research Institute
Kyeong Ja Kim	Korea Institute of Geoscience and Mineral Resources
Michael Kirsch	LaRC/NESC
Christine Knudson	GSFC
Georgiana Kramer	Planetary Science Institute
Linda Krause	MSFC
Angela Krenn	KSC
Joseph Krypel	MSFC
Alton LaBrecque	NA
Thomas Lagarde	Space Architecture
Chris Lauber	Lockheed Martin
Samuel Lawrence	JSC
Sue Lederer	JSC
Joohee Lee	KARI
Pascal Lee	Mars Institute, SETI Institute/ARC
Dan Lester	Exinetics
Joel Levine	College of William and Mary
Rebecca Levy	HQ
Brian Lewis	JSC
Lauren Liddell	ARC
Angel Lopez	MSFC
Ignacio Lopez-Francos	ARC
Martin Losekamm	Technical University of Munich
Kelly Luker	
P Lunn	JPL
Kennda Lynch	Lunar and Planetary Institute
Jane MacGibbon	University of North Florida
Foram Madiyar	Embry Riddle Aeronautical University
Prasun Mahanti	Arizona State University
Neil Mallik	HQ
Jason Maraia	JSC/The Aerospace Corporation
Kevin Margeson	ASU
Alexandra Marnot	Georgia Institute of Technology
Ana Martinez	University of Texas at El Paso
Vinita Marwaha Madill	Rocket Women
James Mastandrea	JHU APL
Mark Matsumura	GSFC
Alexis Maurel	University of Texas at El Paso
Jim May	The Boeing Company
Carey McCleskey	KSC
Mark McConnell	University of NH/Southwest Research Institute

Attendee	Affiliation/Company Name
Amourette McDonagh	Black Moon Space Technology, LLC
Francesca McDonald	ESA
Anna McElhannon	Intern
Shawn McEniry	MSFC
Mark McInerney	GSFC, ESDIS
David McKenzie	MSFC
Chel McMahon	Metalunar
Katie McTigue	ARC
McKayla Meier	University of Idaho
Tina Melton	MSFC
Namishka Mendonca	St. Xavier's College, Mumbai
Marit Meyer	GRC
Eric Michaud	MIT
Joseph Minow	MSFC/NESC
Zara Mirmalek	ARC/BAER
Jason Mitchell	HQ, Space Communications & Navigation (SCaN) Program
Joe Mobilia	Lockheed Martin ATC
Thomas Moody	JSC, EHP
Luis Mora	ET40
Jon Morse	ASTRONETX PBC
Dwight Mosby	HP20
Kausik Mukhopadhyay	University of Central Florida
Alexis Muniz	
Sunny Narayanan	Florida State University
Shyama Narendranath	Indian Space Research Organisation
Issa Nesnas	JPL
Tiffany Nickens	MSFC
Chris Nie	Sierra Space
Shabnam Nikbakhsh	University of Oulu
John Norbury	LaRC
Michael Nord	JHU APL
Tyler Nord	KSC, NE-TE
George Norris	MSFC
Anthony Nunez	CardioVox
Jose Nunez	KSC
Leo Nyman	Aalto University
Hannah O'Brien	Jacobs
Jonna Ocampo	University of Florida
Molly O'Connor	ARC
Thomas Orlando	Georgia Institute of Technology
Rajae Ouherra	
Joey Palmowski	Honeybee Robotics
Lenny Paritsky	MIT Haystack Observatory
Cheol Park	LaRC
Justin Park	Intergalactic Education

Attendee	Affiliation/Company Name
Patricia Maloney	The Aerospace Corporation
Ruby Patterson	University of Houston
Ben Pearson	Lockheed Martin
Anuhansi Pelawatta	Rajarata University of Sri Lanka
Steve Petrinec	Lockheed Martin ATC
Noah Petro	GSFC
James Phillips	KSC
Jorge Pineda	JPL
Ronald Polidan	Lunar Resources, Inc.
Cecilia Poon	
Jamie Porter	JHU APL
Dennis Poulos	Poulos Air & Space, Inc.
Tracie Prater	MSFC
Wayne Pryor	Space Environment Technologies
Allison Quesenbery	MSFC
Aleksandra Radlinska	
Kristine Ramos	The Boeing Company
Elonsio Rayos	JSC
Christian Ready	Townson
Ethan Reid	JSC
Sara Rengifo	MSFC
Kurt Retherford	Southwest Research Institute
Charles Reynerson	JPL
Seth Rhodes	HVRND LLC
James Rice	School of Earth and Space Exploration, Arizona State University
Diane Risdon	HQ/BryceTech
Gemma Rius	IMB-CNM-CSIC
Raja Roy	New Jersey Institute of Technology
Samit Roy	University of Alabama
Anna Maria Ruby	KSC
Josiah Ruelas	KSC/Exploration Ground Systems (EGS)
Margarita Safonova	Indian Institute of Astrophysics
Chris Salvino	University of Arizona
Tara Samuels	ARC
Melissa Sampson	Self
Arianna Sanchez	HQ
Samalis Santini	JHU APL
Hannah Sargeant	University of Central Florida
Jacek Sawoniewicz	JPL
Prabal Saxena	GSFC
James Schier	HQ
Juergen Schlutz	ESA
Gregory Schmidt	ARC
Harrison Schmitt	
Marius Schwinning	ESA

Attendee	Affiliation/Company Name
John Scott	NASA/STMD
Phil Scott	Space Dynamics Laboratory
Tim Scott	DuPont
Megala Senthilkumar	ISRO
Alejandro Serrano Borlaff	NASA/ORAU
Catherine Sham	
Lynda Shook	
Sourabh Shubham	University of Maryland, College Park
Joseph Silk	Johns Hopkins University
Joel Sills	JSC/NESC
Niharika Singh	KGMU, Lucknow, India
Anze Slosar	Brookhaven National Laboratory
Thomas Slusser	Jacobs Technology, Inc.
Phillip Smith	GRC
James Spann	HQ
Ron Spencer	JSC
Jessica Spoto	Astrobotic
Steve Squyres	Blue Origin
Erik Stalcup	GRC
Vitalii Stoliarchuk	State Design Office "Yuzhnoye"/ Oles Honchar Dnipro National University
Philip Stooke	University of Western Ontario
Timothy Stubbs	GSFC
Abhijith Sukumaran	Florida International University
Gabriel Swiney	HQ
Mark Terrone	KSC/NESC
Alexandria Terry	NGA
Donatella Tesei	
V S Devika Thampuratty	
Scott Tingle	JSC
Stefan Tomovic	KSC
Joseph Toth	KSC
Doyle Towles	Peraton
David Traore	ORBIT
Apoorv Tripathi	University of Delhi
Prateek Tripathi	Indian Institute of Technology, Roorkee
Max Tsuizaki	George Washington University
Seamus Tuohy	Dyentics
Thomas Uhlig	German Space Operations Center (GSOC), DLR
Camilla Urbaniak	JPL
Azita Valinia	GSFC/NESC
Gerard Van Belle	Lowell Observatory
Chris Vande Zande	JSC
Harri Vanhala	HQ
Indhu Varatharajan	Stony Brook University
Miguel Angel Vargas Cruz	GRUPO ALIANZA EMPRESARIAL

Attendee	Affiliation/Company Name
Kenny Vassigh	Caylan Space, Inc.
Muthu Venkatesh S	
Michaela Villarreal	Northrop Grumman
Cameron Wales	NGA
Robert Wallace	Xtreme Worksite Fasteners, LLC
Jerry Wang	Spaceport Technologies Office
Sean Wang	National Institute of Aerospace
Xu Wang	University of Colorado, LASP
Lisa Watkins	MSFC
Renee Weber	MSFC
Dawn Whitaker	Purdue University
Nicholas White	Space Science Solutions
David Williams	JSC
Jason Williams	JPL/California Institute of Technology
Ron Wilson	JPL
Tim Wilson	LaRC/NESC
Sarah Withee	JHU APL
Alexandra Witze	Nature
Edward Wollack	GSFC
Marc Wolt	Radboud University
Daniel Wrench	Victoria University of Wellington
Athena Wu	SWR Technology, Inc.
Shu-Chieh Wu	ARC/San Jose State University
Dr. Alhassan Yasin	JHU APL
Aaron Yung	GSFC
Nancy Zeitlin	KSC
Ming Zhang	Florida Institute of Technology
Xiaoduan Zou	Planetary Science Institute

Appendix B. Workshop Agenda


National Aeronautics and Space Administration

UNIQUE SCIENCE
FROM THE MOON IN
THE ARTEMIS ERA WORKSHOP
June 7-9, 2022

NASA KSC Visitor Complex Debus Conference Center and online

Sponsored by the NASA Engineering & Safety Center (NESC)

June 7, 2022

9-11am EDT
Opening Remarks – Tim Wilson (NESC Director)

Keynote Speech – Scott Tingle (NASA Artemis Astronaut & NESC Chief Astronaut)

Objectives of the Workshop and Deliverables – Azita Valinia (NESC Chief Scientist)

Lunar Discovery & Exploration Program and Near-term Artemis Science – Joel Kearns (Deputy Associate Administrator for Exploration, NASA Science Mission Directorate)

Overview of Artemis Program… and How it Enables Science – Jake Bleacher (NASA HQ)

Unique Science from the Moon Overview – Jim Green (NASA)

Break 11-11.15am EDT

11.15am-2.30pm EDT (includes lunch break)
Science Concept Case Studies already funded by NASA SMD & STMD – Moderated by Nick White (Webex moderator: Mark Matsumura)

Focus is on low frequency radio telescope concepts that is identified as an area of discovery in Astro2020 and currently of high interest to both NASA and DoE, as well as heliophysics science applications.

- LuSEE – Stuart Bale (U. of California, Berkeley)
- FARSIDE – Jack Burns (U. of Colorado, Boulder)
- Lunar Crater Radio Telescope (LCRT) – Saptarshi Bandyopadhyay (JPL)
- FarView – Ron Polidan (Lunar Resources Inc.)
- Discussion

Break 2.30-2.50pm EDT

2.50-4.45pm EDT
Round table discussion - Moderated by Jack Burns (Webex moderator: Mark Matsumura)

- International Participation – Marc Klein-Wolt (Radboud University, Netherlands)
- Inter-Agency Activities with DoE – Anže Slosar (Brookhaven National Lab)
- Spectrum Environment and Management for Radio Observations – Cathy Sham (NASA Lunar Spectrum Manager)
- Site Selection for Radio Telescopes – Jack Burns (U. of Colorado)
- Discussion

4.45-5pm EDT
End of Day Wrap Up – Take-Aways Azita Valinia & Nick White

6.30pm Workshop Dinner (Fishlips Waterfront Grill – Cape Canaveral)

June 8, 2022

9- 10am EDT
Keynote Speech: Synergy between Robotics and Human Exploration – John Grunsfeld (Former NASA SMD Associate Administrator and astronaut)

10- 10.20am
Break – Workshop Photo

10.20am-12.30pm EDT
Challenges of the Lunar Environment - Moderated by Jon Haas (Webex moderators: Tim Brady and John Hanson)

- Dust and Charging – Kristen John (NASA JSC) et al.

- Extreme Thermal Environment –Erik Stalcup (NASA GRC), Angela Krenn (NASA KSC) et al.
- Power Generation and Storage – Ryan Edwards (NASA GRC) et al.
- Lessons Learned for Instrument Design & Deployment from Apollo Era - Harrison Schmitt

12.30-1.30pm EDT Lunch Break

1.30-4.15pm EDT

Challenges associated with Human Intervention involving Assembly and Servicing of Scientific Experiments - Moderated by John Grunsfeld and Mike Hess (Webex Moderators: Mark Terrone and Chris Broadaway)

- Needed Human Space Flight Infrastructure – Carey McCleskey (NASA KSC)
  - Surface Architecture Functions Associated with Sustained Human/Robotic Science Operations
  - Surface Site Planning - Science Objectives, Constraints and Considerations (Base Camp vs. Sortie)
  - Overview Human/Robotic Operations and Support Functions
  - Surface Science Facility Deployment - Cargo/Material Handling, Construction, and Assembly Considerations
  - Robotic and/vs Human Deployment of Science Facilities
- Astronaut Requirements for Assembly and Servicing – Jackie Kagey (NASA JSC)
  - Human space flight infrastructure
  - EVA requirements
  - Robotics interaction
  - EVA onsite activities, identification of sites, maintenance
- Cost Challenges and Opportunities – Nick White, Carol Grunsfeld, Jay Bookbinder
  - Partnership Model – Nick White
  - Task Based (e.g., Build, Repair) Human vs. Robotics – Jay Bookbinder
  - Infrastructure and Capabilities Strategic Investments – Carol Grunsfeld

4.15-4.30pm EDT

End of Day Wrap Up – Takeaways, Azita Valinia & Nick White

6.30pm Workshop Dinner (Grills Seafood Deck – Cape Canaveral)

June 9, 2022

9am-1pm EDT

Engineering Challenges and Discussion – Led by Jon Haas (Webex moderators: Tim Brady and John Hanson)

- Communication & Navigation – Jim Schier (NASA HQ) et al.
  - LunaNet Overview
- Worksite Design and Lighting – Charlie Dischinger et al. (NASA MSFC)

Engineering challenges summary and risk mitigation approaches

Capabilities and Infrastructure Summary and Discussion – Led by John Grunsfeld & Mike Hess (Webex moderators: Mark Terrone and Chris Broadaway)
Robotics delivery (CLPS), what could CLPS 2.0 look like in 2030+? (assembly and servicing of experiments using a combination of robotics and human intervention)

- Astronaut assembly and servicing (Artemis)
- Sustained presence capabilities (Artemis Base Camp)
- In Situ Utilization applied to science
- Maintaining radio quiet environment
- Robotic vs human development of science facilities (trades and benefits)
    - What is the role of humans in the process?
    - How much value do humans add in the process? Risk and cost comparison?
- Sensors and instrumentation - Buildup & Planning, Operations, Cleanup

Drivers for Artemis Systems Requirement and Discussion – Led by Renee Weber & Nick White (Webex moderator: Mark Matsumura)

- Leveraging the Artemis infrastructure
- Spectrum of robotic vs human assembly and servicing
- Engineering challenges: knowledge gaps
- Required investments

Workshop Integration and Final Report – Azita Valinia and Nick White

- Report outline and writing assignments

Wrap Up – All

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
11/10/2022

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Unique Science from the Moon in the Artemis Era

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Valinia, Azita; Grunsfeld, John M.; Hess, Michael G.; Green, James; Schier, James; Haas, Jon P.; Weber, Renee C.; Dischinger, Charles; White, Nicholas E.; McClenskey, Carey M.; John, Kristen K.; Edwards, Ryan D.; Stalcup, Erik J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
869021.01.23.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
NESC-RP-22-01729

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-20220017053

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category Lunar and Planetary Science and Exploration
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Since the beginning of the space age, the Moon has been proposed as a platform for astronomy. The Moon provides unique capabilities for astrophysics observations. NASA's Artemis plan to return humans to the Moon in the mid-2020s in a sustainable manner provides an opportunity to advance synergistic approaches between human and robotic exploration. This NASA Engineering and Safety Center (NESC) workshop assesses the feasibility and value proposition of using the Moon as a location for performing unique science observations, leveraging Artemis-era infrastructure while evaluating risks and key engineering challenges.

15. SUBJECT TERMS
NASA Engineering and Safety Center; Moon; Artemis; Astrophysics; Robotic Exploration; Human Exploration

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		
U	U	U	UU	101

19a. NAME OF RESPONSIBLE PERSON
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19b. TELEPHONE NUMBER *(Include area code)*
(443) 757-5802

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18