The Impact of Lunar Dust on Human Exploration Workshop
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The Artemis Program: Enabling Human Exploration of the Moon

Brad Bailey, NASA Headquarters
Jacob Bleacher, NASA Headquarters
Samuel Lawrence, NASA Johnson Space Center
Erin Mahoney, Stardog Union
Julie A. Robinson, NASA Headquarters

INTRODUCTION: ARTEMIS OBJECTIVES AND BASIC ARCHITECTURE

The Artemis program is a collective effort that NASA is leading to explore more of the Moon than ever before with a thorough investigative approach combining science and human exploration objectives. In this paper, we provide a summary of NASA's next decade of lunar exploration plans, as of June 2020, to set the stage for these Lunar Dust Workshop proceedings.

At the Moon, a coalition comprising NASA, international space agencies, and global space industry partners will establish an interconnected presence in orbit and on the surface (Figure 1). On the surface, robotic landers will deliver science investigation payloads prior to a human return in 2024. In orbit, assembly of the Gateway will create a permanent command module for all lunar activities, as well as a port for visiting astronauts and spacecraft.

Figure 1. As part of the Artemis program, NASA envisions a continuum of surface hardware and operations including astronaut extravehicular activities, unpressurized and pressurized rovers, stationary habitats, and associated support systems.

Artemis will commence with robotic precursor missions deployed to lunar orbit and the lunar surface beginning in 2021 to return new information about the lunar environment and inform future science investigations and human mission planning. The Artemis I and Artemis II flight tests of the deep space human transportation system—the Space Launch System rocket, Orion crew vehicle, European Service Module, and supporting ground systems—will prepare for Artemis III, which will include the first human lunar landing of the 21st century. NASA has accepted this challenge land the first woman and next man touch down on the South Pole of the Moon by 2024, as the first of multiple missions that will advance scientific knowledge and human exploration capabilities.

Bots before Boots

Breakthrough discoveries from the Lunar Reconnaissance Orbiter (LRO) and Lunar CRater Observation and Sensing Satellite (LCROSS) have reinforced the Moon's status as a cornerstone of planetary science. The Moon is not a barren and dormant world – it is a resource-rich world with unparalleled opportunities for scientific discoveries and commercial activity (Keller et al., 2016; LEAG, 2016, 2017a,b, 2018). Establishing a rigorous program of lunar surface exploration will advance American interests by opening the lunar frontier to the energy and vitality of American enterprise, enabling significant scientific advances in the process.

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) CubeSat will enter a near-rectilinear halo orbit (NRHO) around the Moon, rotating together with the Moon as it orbits Earth. The NRHO will be the initial operating orbit of the Gateway and was selected because of its gravitationally balanced advantages that require minimal propellant to maintain the spacecraft. CAPSTONE will demonstrate how to enter into and operate in NRHO as well as test a new navigation capability. This information will help reduce logistical uncertainty for Gateway, as NASA and international partners work to ensure astronauts have safe access to the Moon's surface.

Through NASA's Commercial Lunar Payload Services (CLPS) initiative, 14 U.S. companies are on contract and eligible to bid on science and technology payload deliveries to the Moon. Astrobotic and Intuitive Machines each have one task order award for deliveries in 2021. Astrobotic will carry 11 payloads to Lacus Mortis, a larger crater on the near side of the Moon, and Intuitive Machines will carry five payloads to the Aristarchus Plateau, a volcanic terrain in Oceanus Procellarum that is one of the Moon's largest ore deposits (Coombs and Hawke, 1991; Gaddis et al., 2003). Exploring the polar regions has been a high exploration priority for the past four decades (e.g., Taylor and Spudis, 1990; Nozette et al., 1996, 2001; National Research Council, 2007; NASA Advisory Council, 2007; Lunar Exploration Analysis Group, 2016, 2017, 2018; Jawin et al., 2018; Li et al., 2018). To that end, Masten Space Systems has been awarded one task order to deliver and operate eight payloads – with nine science and technology instruments – to the lunar south polar region in 2022. And in June, NASA announced that Astrobotic would also deliver the agency's Volatiles Investigating Polar Exploration Rover (VIPER) to the south polar region in 2023. VIPER and the Masten delivery will become the first surface explorers near the South Pole of the Moon and will provide ground truth observations of the potential polar volatile deposits, achieving both scientific and exploration objectives.

The Artemis I uncrewed flight test scheduled for 2021 will carry 13 CubeSats onboard, five of which will be deployed to the lunar vicinity.

- Skyfire will perform a lunar flyby of the Moon, taking sensor data during the flyby to enhance our knowledge of the lunar surface
- Lunar IceCube will search for water ice and other resources at a low orbit of only 62 miles above the surface of the Moon
- Lunar Flashlight will look for ice deposits and identify locations where resources may be extracted from the lunar surface
- LunaH-Map will map hydrogen within craters and other permanently shadowed regions throughout the Moon's south polar region
- Cislunar Explorers' novel propulsion system using inert water will be tapped to carry out a gravity assist with the Moon, and then be captured into lunar orbit.

The first two components of the Gateway—the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO) will be integrated for launch in 2023 and pre-loaded with two science instrument suites. ESA's (European Space Agency) European Radiation Sensors Array (ERSA) will help provide an understanding of how to keep astronauts safe by monitoring the radiation exposure in Gateway's unique orbit. The Heliophysics Environmental and Radiation Measurement Experiment (HERMES), NASA's space weather instrument suite, will observe solar particles and solar wind.

These early Artemis robotic investigations will increase our knowledge base about the lunar environment and confirm the nature of the Moon's vast resource potential, informing planning for future human and robotic expeditions, including planning for Artemis astronauts beginning in 2024.

The Human Transportation and Logistics Supply Chain to the Moon

NASA's Space Launch System rocket, Orion crew vehicle, and supporting ground systems will be the backbone for deep space transportation. The first integrated flight test, Artemis I, will be an uncrewed flight to validate the systems' performance in deep space and Orion's thermal resilience to Earth-return speeds.

Artemis II will be a crewed flight test to validate the life support systems, various communications systems and scenarios, and manual flight controls in a rendezvous and proximity operations demonstration. Astronauts aboard Orion for Artemis III will rendezvous with a Human Landing System in lunar orbit to make their descent to the lunar South Pole. NASA has awarded three companies, Blue Origin, Dynetics, and SpaceX to begin refining their Human Landing System designs.

The Artemis III crew may rendezvous with the lander at the Gateway or may board the lander directly from Orion. As more modules are added to the Gateway—many provided by international partners—the spaceship will become more and more capable as a long-term science and exploration platform in deep space. Additions to Gateway will amplify the robotic assistance for the mostly dormant ship, add more living space for extended crew expeditions on and around the Moon, and support Mars mission simulations.

While the Space Launch System will launch crew aboard Orion, and potentially carry co-manifested payloads to lunar orbit, the increasingly capable commercial launch market will be the workhorse of lunar development. Commercial rockets are expected to carry Gateway modules, CLPS landers, and many other surface and orbital assets.

ARTEMIS SCIENCE STRATEGY

NASA's Science Mission Directorate is leading the Artemis science strategy. Priorities for the overarching strategy are based on a variety of sources, including Decadal Survey objectives as outlined in the 2013-2023 Planetary Decadal survey (NRC, 2011), the 2007 National Research Council Report on the Scientific Context for the Exploration of the Moon (NRC, 2007), the United States Lunar Exploration Roadmap maintained by the NASA Lunar Exploration Analysis Group (LEAG, 2016), and the 2018 LEAG Advancing Science of the Moon Report (LEAG, 2018). These reports all demonstrate that the Moon offers rich opportunities for exploration, with numerous opportunities to impact our understanding of the Solar System, the Universe around us, and our place within it.

Artemis science goals will be driven by these established community priorities and will uphold all NASA research standards, including competitive selections and open data policies. SMD will foster competitive research by creating lunar investigation opportunities. The science themes that have been clearly articulated by the community and which NASA intends to enable are:

- Understanding planetary processes
- Understanding volatile cycles
- Interpreting the impact history of the Earth-Moon system
- Revealing the record of the ancient Sun
- Observing the universe from a unique location
- Conducting experimental science in the lunar environment
- Investigating and mitigating exploration risks to humans

Achieving these research goals will create a bold new era of human discovery, and require a coordinated effort among NASA's mission directorates to ensure that these high-level goals are met in a flexible and sustainable manner, all while leveraging the full capabilities of the domestic and international research communities. The nature of science is iterative. It is expected that as Artemis crews reach the lunar surface and conduct fieldwork and fundamental research that answer longstanding planetary science questions and redefine our understanding of the Solar System, new hypotheses and research goals will arise that can make use of the regular, sustained access to the lunar surface provided by the Artemis program, and then in turn become reflected in updated community science priorities. Based on the consensus expressed in the community documents used to guide the creation of the Artemis Science Objectives, it is expected that discoveries made on the Moon will have dramatic impacts on our understanding of the entire Solar System.

The CLPS initiative and the Artemis I secondary payload suite have already established the initial pipeline to deliver science and technology payloads to the lunar surface and to orbit. As the Gateway comes online, long-term orbital investigations can begin. The next objective will be to develop surface mobility, robotic sample return, and systems to enable lunar nighttime survival to expand and enhance scientific investigations, which will harness not only NASA contributions, but also those of international partners who may send instruments or rovers to the Moon.

For human and human-robotic science beginning with Artemis III in 2024, SMD is leading development of scientific activities in the areas related to field geology, sample collection and return, tools and instrumentation, access to previously unexplored cold traps, and the lunar far side. Creating a pathway to advance low-TRL components and sensors is also part of the Artemis science implementation strategy.

SURFACE ASSETS

Science at the Moon will be enabled by unprecedented time and access of Artemis crews to sites on the lunar surface. Prepositioned assets are an important consideration that will leverage CLPS delivery capabilities and relieve mass margins aboard the Human Landing System. Prepositioned assets could include geologic sampling tools, containers for sample return, instruments for geologic analyses, or experiments for crew deployment. Sample documentation equipment such as tags, barcodes, and cameras will also be necessary and can be prepositioned.

The Artemis III surface expedition astronauts will be confined to the exploration range dictated by their spacesuit capabilities on each spacewalk. For later expeditions, NASA plans to preposition a lunar terrain vehicle (LTV)—an unpressurized rover—to vastly expand the exploration range and allow a more diverse sampling of regional surface and subsurface specimens.

Artemis III astronauts will spend 6.5 days on the surface, living inside the lander's crew cabin that they will use to launch back to lunar orbit to rendezvous with Orion. As more surface infrastructure is added, future expeditions could last multiple lunar days or longer. For example, a pressurized rover would combine habitation and mobility, allowing astronauts to rove tens of kilometers from the lander in a plainclothes environment, donning their spacesuits only for spacewalks. Similarly, a surface habitat would extend the amount of time astronauts can live and work in a shirtsleeve environment, donning their suits for moonwalks on foot, in the lunar terrain vehicle, or in the pressurized rover.

SURFACE OPERATIONS AND MOONWALKS

The number of extravehicular activities (EVAs, or moonwalks) and their durations will depend on the down mass permitted on the human landing system and the allocation of resources for the spacesuits and mobile life support systems. NASA has established a minimum requirement of one planned and one contingency EVA for Artemis III, but the goal is for crew to do at least four moonwalks with reserves available for a fifth contingency EVA. As the mission draws nearer and the landing site or region is more defined, NASA will begin to prioritize specific science activities for the surface expedition crew.

Each moonwalk will begin with tool selection and preparation for the day's investigations and will end with a decontamination process to reduce the amount of lunar dust that may be tracked from the spacesuits into the crew cabin.

SAMPLE ACQUISTION AND CURATION

The Artemis sample curation plan development is yet another multi-directorate effort to address curation tools, containers, and transport from the lunar surface back to Earth. Because the lunar surface infrastructure is expected to grow throughout the 2020s, the plan includes a phased approach that begins with minimal assets assumed to be available for Artemis III, with gradually increasing capabilities based on additional assets throughout the decade. NASA may have the opportunity to preposition geological sampling tools and storage containers using CLPS landers

To enable a robust program of sample acquisition and curation and provide seamless scientific access to Apollo and Artemis samples, extensive Artemis sample curation planning has already been started by the NASA Astromaterials Research and Exploration Science division at the NASA Johnson Space Center (Mitchell et al., 2020).

In addition, astronaut geology field training will evolve for the next cohort of astronauts to be specifically tailored to Artemis program needs to maximize the value of astronaut fieldwork in the unique lunar environment. In this training, astronauts learn many of the decision processes required for proper geological protocol and prioritization based on mass constraints for their ascent back to lunar orbit. They learn what types of samples to collect, how much of each, and how to properly document and store them for transport back to Earth (Eppler et al., 2016)

Conclusion

The Moon is a resource-rich, readily accessible target for future United States human and robotic missions that will enable fundamental scientific advances impacting our understanding of the Solar System and the Universe around us, enable commercial opportunity, increase our space-faring capability, and in so doing promote an enduring human presence beyond low-Earth orbit. The Artemis program, which will establish 21st-century American access to the lunar surface, is designed to achieve a variety of ambitious science activities that will spur this bold new era of human discovery.

Mitigation of the effects of dust on hardware and human explorers is an important aspect of achieving a lasting human presence in space. Establishing the capabilities to live and work productively on other worlds for gradually increasing time intervals with synergy across orbiting and surface assets all feed forward to how we may conduct human exploration on the surface of Mars and other destinations (LEAG, 2016). Workshops such as this one serve to highlight the value of scientific participation in human spaceflight endeavors and promote cross-disciplinary communication that will undoubtedly grow in importance as the Artemis program continues.

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