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Future instruments and sustainable outposts for deep space, Moon and Mars: Highlights and lessons from geologists supporting Apollo astronauts

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A fundamental goal of international human and robotic space exploration is to establish human outposts and bases on the Moon and Mars. We seek to provide a *planetary science* perspective on lessons learned from the Apollo Lunar Exploration Program.

1) Why?: What is the legacy, the long-term impact of our efforts? Apollo revealed the Earth as a planet, showed the inextricable links of the Earth-Moon system, and made the Solar System our neighborhood. We now ask: What are our origins and where are we heading?: We seek to understand the origin and evolution of the Moon, the Moon's links to the earliest Earth history, and its lessons for exploration and understanding of Mars. These perspectives impel us to learn the lessons of off-Earth, long-term, long-distance resupply and self-sustaining presence, in order to prepare for the exploration of Mars.

2) Where?: The combination of Transformative Lunar Science (TLS) questions [1] and exploration operational requirements compel us to explore the South Polar Region (SPR) of the Moon. The *scientific goals* are clear: 1) What is the origin, nature and abundance of polar volatile deposits and what do they tell us about internal/external sources and volatile history? [2-3] 2) What is the nature/composition/age of the South Pole-Aitken basin, and how does this inform us about lunar interior/chronology/bombardment history, and early Solar System dynamics? [4-5] The *scientific objectives* are: 1) explore, document/sample volatile deposits in permanently shadowed and stratigraphically related regions. 2) explore/document/sample/date SPA ejecta/pre-SPA crustal materials. *Exploration operational goals/objectives* are clear: 1) Define regions that optimize realization of scientific goals/objectives. 2) Define regions of continuous/near-continuous solar illumination to provide power to survive lunar night, establish long-term presence. 3) Explore SPR to establish the nature/abundance/mode of occurrence/"grade" of candidate volatile deposits. 4) Characterize surface physical properties/trafficability in order to optimize scientific/operational activities. 5) Prepare for dedicated human/robotic exploration missions to other parts of the Moon and Mars. 6) Test nascent technologies required for sustained human Moon/Mars presence (habitation/energy storage/radiation protection/ISRU).

3) How?: Necessary is the development of a conceptual/operational framework built on a firm foundation of existing knowledge and data, and inclusion/optimization of new ideas/technologies. This permits us to continue the exploration to the next logical stages following the remarkably successful Apollo Lunar Exploration Program and multiple followon orbital/surface robotic missions. What are foundation pillars? a) Science and Engineering Synergism (SES): Apollo was successful because of the shoulder-to-shoulder engineer-scientist work culture that developed, and enabled longer-duration stay times and EVAs, significant mobility, additional equipment and experiments, and significantly greater sample return. SES requires concentrated/dedicated effort, but the rewards are clear, essential and *synergistic*. SES maps out into operations at all levels of mission planning and execution. b) Human-Robotic Partnerships: Exploration is not a technique contest, but a partnership. The US sent 21 robotic missions prior to Apollo 11. The key to continual success lies in developing an architecture that complements and optimizes robotic and human capabilities. c) Exploration Guidelines: Define human and robotic strengths and weaknesses, and optimize exploration plans. Longer-term stays mean both increased interactions with Earth and exploration independence of the Astronauts. Avoid "creeping determinism" [6], and encourage the Apollo T^3 approach (Train 'em/Trust 'em/Turn 'em loose). Science and operational goals and objectives require exploration of broad areas: build in extensive Apollo LRV-like mobility. New remote-sensing technologies will enable more in situ characterization, sample analysis and selection but Earth laboratory technology advances will always outpace in situ analysis. Build in significant sample return mass from the beginning. d) Exploration Architectures: Individual missions are viewed as integrated elements in an operational strategy/architecture that is designed to accomplish the overarching goals. Candidate elements: I) *Precursor* (What do we need to know before we send humans?). II) *Context* (What are robotic mission requirements for final landing site selection/regional context for results?). III) *Infrastructure/Operations* (What specific robotic capabilities are required to optimize human scientific exploration performance?). IV) *Interpolation* (How do we use robotic missions to interpolate between human traverses?). V) *Extrapolation* (How do we use robotic missions to extrapolate beyond the human exploration radius?). VI) *Progeny* (What targeted robotic successor missions might be sent to the region to follow up on discoveries during exploration and from post-campaign analysis?). The NASA Commercial Lunar Payload Services (CLPS) Program complements the Artemis Program in this manner. e) Flexibility and Adaptability: *Science is the exploration of the unknown.*

Site Selection/Traverse Planning Guidelines: Landing site selection always involves a balance of mission goals and objectives, and landing/operation safety/success. Science and Engineering Synergism (SES) is the key to this success as demonstrated during Apollo, and should be implemented throughout the exploration architecture. The same principles apply to traverse planning. SES ensures that science/engineering data needed for key decisions will be available and optimizes decisions. SES also optimizes the long-term goal of lunar base siting: for example, Mons Malapert, an inviting target for base siting due to favorable illumination/power, is difficult to traverse with Lunokhod and Apollo LRV-type vehicles [7].

Surface Operations: New instrumentation and technologies will significantly enhance exploration planning and accomplishment of goals. A multispectral laser reflectometer on the surface can confirm the presence of water ice and its location and distribution on scales relevant to human operations (cm to m), and be used to direct sampling and ISRU efforts undertaken by Artemis astronauts, a capability [9] highly complementary to orbital approaches. The parallel operations of robotic rovers, CLPS payload deliveries, and human activities will require continuous engineering and science operations/analysis centers on Earth. Lessons from the ISS should be incorporated, while also recognizing the human exploration capabilities of the Astronauts on the Moon [6].

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