HUMAN AND ROBOTIC OPERATIONS PLANNING FRAMEWORK FOR EXECUTING ARTEMIS LUNAR SCIENTIFIC EXPLORATION. D.B. Eppler[1], D. C. Barker[2], E. Bell[3], C. Evans[4], J. Head[5], M. Helper[6], K.V. Hodges[7], J. Hurtado[8], K. Klaus[9], C. Neal[10], H. H. Schmitt[11] and B. Tewksbury[12]. [1]The Aerospace Corporation, 2525 Bay Area Boulevard, Houston, TX 77058, dean.b.eppler@aero.org, [2]MAXD, Inc., Houston, TX. [3]The University of Maryland. [4]NASA-Johnson Space Center. [5]Brown University. [6]University of Texas, Austin. [7]Arizona State University. [8]University of Texas, El Paso. [9]Lunar and Planetary Institute. [10]The University of Notre Dame. [11]Blue Origin National Team Science Advisory Board. [12]Hamilton College.

Introduction: Field geological exploration conducted on the lunar surface will be the keystone for addressing the open scientific questions. Executing these activities will be complex and expensive, regardless of whether the agent conducting the exploration is human or robotic. Therefore, it is critical that the next steps in lunar scientific exploration be understood in the terms of the goals and preparations required, including crew skill sets and training. This includes the operational approaches necessary to conduct productive and efficient surface science operations, the hardware and training necessary to acquire the appropriate samples and data, and the experience and training required of those involved, both crewmembers on the Moon and operations personnel on Earth. Each of these elements needs to be integrated into mission design, planning, training and execution of Artemis from the beginning, such that science is an integral part of the operation, not a late-stage add-on.

Basic Premise and Applications to Artemis Science: Our premise is that for each open lunar science question, there is a limited range of possible solutions that will provide the desired exploration efficiency, control costs, manage the operational risk to human and robotic crewmembers, and allow for unexpected discoveries. Early analysis of operational approaches and requirements appropriate to each question will identify whether human or robotic assets will improve the chances for mission success. Failure to identify the appropriate approaches will likely lead to a mismatch of the mission assets applied, and will also lead to increased costs and risk by developing assets that are either insufficient to meet the science objectives, or are over-designed and more complex to operate. *The key concept is that we should never send a robot to do a human's job, and never send a human crewmember to do a task more efficiently executed by a robot*.

Human and Robotic Agent Attributes: The two end member agents for conducting surface science operations are humans and robots, either operating in isolation or in tandem. Each agent has both strong points and limitations, and *neither* agent is optimal for *all* exploration science operations tasks. In particular, experience has shown that duplicating the capabilities and efficiencies of experienced field geologists in a robotic agent would likely be more costly than a human mission. The use of human explorers will always be a necessary component of extensive and successful lunar surface exploration

Human agents, when provided with a foundation of field training and experience, provide the most flexible, intuitive and efficient capability to dealing with complex scientific and operational situations, including planning a detailed strategy for sampling/ surveying, analyzing a complex geological locality, post-sample collection analysis, or implementing solutions to unexpected challenges and discoveries. Human explorers are significantly better at developing exploration strategies and modifying those strategies in real-time [1]. Hodges and Schmitt [1] adapted the concept of flexicution [2, 3] to illustrate how field geologic mapping is executed in a terrestrial setting. The value of flexicution has been illustrated in the continued evolution of understanding of the geology of the valley of Taurus-Littrow as the original field geological observations and sampling are continuously integrated with 45 years of sample analysis and remote sensing data [4]. Developing a sufficient grasp of the geographic and stratigraphic setting of returned samples will establish the geologic context necessary for post-mission analysis of samples and data, and will be critical for answering many of the scientific problems identified at this meeting.

In contrast, robotic agents work best in the conduct of routine, repetitive activities during pre- and post-mission investigations – robots do not get bored, they can be designed to repeat the same procedure identically as many times as required, they continue to function as long as they have operational resources such as power and working mechanisms, and are engineered to be fault tolerant. Robots can also be designed to operate in environments that would significantly increase risks to human crewmembers, although more challenging environments will likely increase costs and launch mass. Many of the open lunar science questions can be addressed by robotic science missions executed at multiple localities, such as deploying Moon-wide

ALSEP-type packages. Using robotic agents for operations appropriate to their capabilities will result in recovery of scientific data that might otherwise be limited in a human-only exploration program.

The integration of human and robotic exploration can best be achieved through the use of robotic reconnaissance to set the stage for human landings, and for post-human mission on-going exploration. Precursor robots can assist greatly in exploration planning, and initial site identification and characterization, while continued use of robots after a human crew departs can follow-up on questions raised by post-mission analysis. The question of robotic field assistants has been raised often, but it has never been used as a design driver for a particular robot. Consequently, the present generation of robots involved in planetary exploration (e.g., the Mars Science Laboratory, the Chinese Yutu series move too slowly to be suitable as real time robotic field assistants. A comparison of traverse times between the Apollo Program and the Mars Exploration Rover (MER) is illustrative: it took the Apollo 17 crew three days to put ≈28 km on the Lunar Roving Vehicle odometer, while it took MER Rover Opportunity over 3000 Martian sols to accumulate the same mileage [J. Head, personal communication, 2015]. Clancy [5] correctly stated that humans are exploring Mars, not robots, but the speed of our present approach to robotic operations makes robotic exploration extremely slow compared to the Apollo Program experience. Integration of human crewmembers and robots as complementary field partners remains an illusive goal.

Training and Equipping Human Explorers: Successful lunar scientific exploration in the next decades requires cross-trained crewmembers with backgrounds as pilots, engineers and scientists working with a similarly talented and trained team of flight controllers. The success of the Apollo program has shown both that crewmembers and ground controllers from multiple disciplines can function as a successful, integrated team, provided the appropriate training is undertaken prior to each mission. For Apollos 15-17, this included extensive (>1000 hours) [6] [7] of geologic training in relevant field localities to hone observational and EVA skills within a specific mission context. Future human crewmembers will require similar levels of training to be competent geologic explorers, regardless of their original technical training and experience. This is a critical feed-forward activity to Mars exploration. In recognition of this requirement, NASA has begun training each new Astronaut Class in the fundamentals of field geologic observations, starting with the 2009 Astronaut Class [8], *but extensive follow-on Apollo-style mission-specific field training is not yet part of the approved training cycle for Artemis crews*. This needs to be remedied as soon as possible [9].

In addition to the usual complement of simple hand tools (hammers, rakes, scoops, core tubes, drills) carried on Apollo, the advent of portable analytical equipment has the potential to enhance in-situ sample analysis and collection quality, reduce returned sample mass, and assist on-going planning of future operations. However, these tools must be able to provide meaningful analytical data within the time context of a human mission. Extensive integration times will limit effective use by human agents, and make them more applicable to use by robotic agents or in habitat laboratories. Continued testing of operational concepts for the use of these tools has the potential to significantly improve the science return from human exploration missions.

Summary:

- The Apollo expeditions showed that human crews, well trained in the techniques of field geology and supported by similarly trained flight controllers, can accomplish exceptional science return in spite of significant time constraints.
- It is well within present capability to design ALSEP-type arrays for robotic assembly and checkout, with human crewmembers only used for assembly errors and/or final activation, freeing up crewmembers for exploration efforts.
- The proper mix of human and robotic tasks will greatly improve Artemis science, *provided the decisions are made now for the proper geologic training for the crew and ground teams, and for proper design for robotic systems.*
- Appropriate use of both humans and robots needs to be integrated into mission design, training and execution of Artemis now, not as a late-stage add-on.

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