Tactical and strategic science support for crewed Artemis missions: lessons learned from the BASALT Research Program

D.S.S. Lim[1], S. Chappell[2], K.H, Beaton[2], S. Kobs Nawotniak[3], A.L. Brady[4], Z. Mirmalek[5], A. Sehlke[5], D. Newman[6], D.S. Lees[7], A. Abercromby[8], C.S. Cockell[9], A. Stevens[9], R. Elphic[1], T. Cohen[7], and the BASALT Team. [1] NASA ARC, Moffett Field, CA, Darlene.lim@nasa.gov, [2]KBR/NASA JSC,Houston, TX, [3]Idaho State University, Pocatello, ID, [4]McMaster University, Hamilton, ON, Canada, [5]BAER Institute, Moffett Field, CA [6]MIT, Cambridge, MA, [7]KBR/NASA ARC, Intelligent Robotics Group, Moffett Field, CA, [8]NASA JSC, Houston, Texas [9]UK Centre for Astrobiology, School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3FD, UK.

NASA's Artemis Program plans to return humans to the lunar surface in 2024, beginning with 2-crew sortie missions, followed by the establishment of an Artemis Base Camp (ABC) to support 4 crew for sustained exploration by 2030. Artemis missions will also serve as an analog to test systems for human Mars exploration. Achieving science objectives is one of the cornerstones of the Artemis Program upon which the operations and execution framework will be built. Recent efforts in terrestrial spaceflight analogs provide substantial insight into concepts of operations (ConOps), tools, and techniques to help achieve future lunar and Martian science objectives. Capabilities that facilitate tactical and strategic interactions between crews on the Moon or Mars and Earth-based science teams will enable science accomplishments. While crewmembers will certainly be highly trained, a broader and deeper scientific knowledge will persist on Earth. Hence, determining the best ways to engage remote Earth-based scientists is critical to achieving the best possible science and to enable discovery.

Efforts to provide both real-time tactical and longer-term strategic science support of Artemis missions will require a recognition of the unique operational paradigm associated with exploring the lunar South polar region. Environmental elements, such as lunar surface characteristics, light/shadow dynamics, and variable direct-to-Earth communication links, create operational conditions between the Earth and Moon that must be handled in the design of Artemis science support systems. These unique conditions will directly impact the manner and speed with which the Artemis science team can synthesize and analyze data and produce timely science-driven decisions throughout surface mission operations. If our science team is to affect extravehicular activities (EVAs) on tactical timescales (e.g. during and between EVAs), then it must be able to collectively assimilate and analyze data to provide meaningful input within appropriate timeframes.

The development of science support systems for Artemis will require structured, continuous integration between science, operations, and engineering stakeholders. Part of this effort will include iterative development of ConOps and capabilities that enable efficient and effective cooperation between scientific explorers on the Moon and mission scientists on Earth. These ConOps and capabilities will have to account for and support the varying breadth and depth of science expertise both within the Artemis crew and within the science teams on Earth. As such, it is anticipated that various science support options will be required to facilitate meaningful scientific cooperation during EVA execution (intra-EVA), as well as periods between EVAs (*i.e.*, inter-EVA) and when crew autonomy is required. Our team's work on various analog research programs, and most recently on the NASA SMD PSD P-STAR funded BASALT research program, provides a means to quantitatively and qualitatively examine science support needs for future crewed mission scenarios (see Astrobiology, Vol 19, Issue 3, March 2019 Special Issue for more details). Our findings highlight the importance of operationalizing mission science priorities – that is, by parsing science goals into component parts, it is then possible to thoughtfully construct ConOps and capabilities that support a diverse and interrelated set of scientific mission objectives. This process is non-trivial, but serves to drive-out requirements that result in the seamless integration of science into the overarching exploration efforts.

The operational articulation of the BASALT team's science goals led to the design of both mission and EVA timelines that purposefully incorporated ground assimilation time (GAT) and facilitated strategic and tactical scientific decision making. BASALT EVAs were structured such that scientific data were gathered in systematic stages, creating necessary GAT so the EVA crew had input before beginning their next stage. Staggered information gathering and activities during each BASALT EVA was facilitated by the use of a Dynamic Leaderboard (DL) that was continuously updated as the science team reviewed incoming field data, conferred, and reached consensus on sampling priorities. Additionally, BASALT EVAs were conducted with 2 extravehicular (EV) crew in the field and 2 intravehicular (IV) crew inside a simulated habitat (note: this is the baseline for the ABC, where 2 crew will conduct EVAs from a small pressurized rover and 2 crew will be located in a surface-based habitat). The 2 IV crew split duties, acting as intermediaries with the BASALT Mission Support

Center (MSC) for operations and science, including managing interactions on the DL. The DL was referred to by IV (and conveyed to EV) crewmembers and mission control personnel as needed, enabling EVA crewmembers to maintain situational awareness (SA) and focus on current tasks without continuous interruptions. While essential under communication latency, this method of delivering scientific information and enabling on-going discussion will also be beneficial when providing real-time Earth-based Science Center support during Artemis crewed missions.

The BASALT team also found that communication protocols needed to be developed, in concert with simulated mission expectations, and stress-tested before being incorporated into training and use during each EVA. One example of this can be found in the study by Sehlke et al. (2019) on how to integrate novel handheld scientific instruments for *in-situ* geochemical and petrological analyses into the EVA architecture (Sehlke *et al.,* 2019, p.422, Fig. 18). Consistent monitoring of temporal durations for data acquisition, sharing, interpreting and discussing from the field to the science center was used to elevate SA support needs.

SA sharing relied on technology support that enabled communication, both oral and digital, and mission timeline management. The BASALT program utilized MINERVA, which was a capability that was developed to support scientific planning, monitoring, data archiving, and data exploration, and to create scientific and operational SA for the science team (Marquez et al. 2019). MINERVA provided the science and operations teams with a shared view of EVA plans, collected data and mission status, and thus a means to be highly responsive, as a collective, to emergent exploration conditions. Through MINERVA the science team could use *a priori* generated maps to create and share geospatial information in order to develop scientific traverse plans both before and during the missions. Additionally, the capability served as a digital repository for operational and scientific data, tracking and live monitoring of EV positions, video, photos, sample metadata, and science instrument data. These data could be annotated via integrated, geolocated, and time-stamped digital notes. As well, the BASALT team incorporated and evaluated a series of capabilities to measure their effect on SA and mission science overall. These capabilities included high-resolution panoramic imagery, mobile automated light detection and ranging data, immersive mixed-reality terrain models, and augmented-reality field systems for terrain navigation and annotation. Both MINERVA and these additional science capabilities were developed through a close partnering of the science, operations and technology elements from the beginning of the BASALT program. This integrated work effort required months of careful management and development, and the positive effects of this early team-building work had significant downstream implications towards mission success.

The BASALT science team also constructed a Science Traceability Matrix (STM) as another means to establish and to guide the specific science objectives planned for each BASALT EVA. Individual EVA timelines were baselined prior to the start of each field campaign and then updated daily as new scientific and operational information from that day's EVA was gleaned. Tactical science teams in the MSC were able to systematically assimilate incoming field data and formulate recommendations in near real-time (across Mars-relevant latencies), and then evaluate the EVA's progress towards the science goals articulated within the STM. Parallel strategic science teams proposed amendments to future EVA plans to meet overall mission objectives. The design of the MSC included a clear delineation of roles and responsibilities of all personnel and how those individuals were physically arranged within the MSC space (Payler et al. 2019). This structure enabled scientific discourse to be prioritized; specialist leads could streamline the discussion of scientific observations and findings to meet the mission cadence and key decision timeframes.

Throughout the 4+ year span of the BASALT program the team conducted multiple Engineering Readiness Tests and Operational Readiness Tests. Throughout each of these test periods, and during the missions, qualitative and quantitative metrics were collected to capture actionable feedback that could be used to improve and evolve science support systems. This structured and milestone-driven iterative development process enabled project scientists to collaborate with operations and engineering participants to systematically test and improve BASALT ConOps and supporting capabilities. This type of integrated development cycle would enable the design and development of science support systems that will meet the mission needs of near-term Artemis missions, and future crewed missions to Mars.