A SERIES OF ROBOTIC AND HUMAN ANALOGUE MISSIONS IN SUPPORT OF LUNAR SAMPLE RETURN.
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Analogue mission overview: In response to a Request for Proposals issued by the Canadian Space Agency, our team was awarded a contract to carry out an analogue mission campaign entitled Impacts: Lunar Sample Return (ILSR) "An Analogue Mission in Support of Future Sample Return Missions to the South Pole–Aitken (SPA) Basin". This analogue mission campaign comprises a series of scientific, operational, and technical objectives that address CSEW6 Objective PG-L-4 ("estimate the rates, processes and effects of lunar impact cratering"), namely:

- The ages and rates of impact bombardment on the Moon and, by extension, for the entire inner Solar System (PG-L-4-Investigation 1);
- Shock processes in lunar materials and terrestrial analogues (PG-L-4-Investigation 2);
- Impact ejecta emplacement processes (PG-L-4-Investigation 3);
- Resources within lunar impact craters.

The return of samples from the SPA basin on the Moon is a high priority for the Canadian, U.S., and international planetary science communities [1].

In order to prepare and train for potential future robotic and human sample return missions, we carried out a series of analogue missions on Earth that developed and tested operational procedures and techniques.

One of the main goals of this analogue mission campaign was to develop remote sensing analysis, mapping, site selection, geochemical analysis and sampling protocols for identifying and collecting specific target materials. This required a detailed set of decision-making processes for outcrop mapping, site targeting, sample selection, and sample acquisition. We aimed to re-evaluate the optimal combination of robot and/or human workers for each task, be it astronaut-only, astronauts with robotic assistants, or unmanned robotic surrogates. Ultimately, analogue missions are important for highlighting the technological developments that are needed to sustain the ongoing exploration of our solar system. For a more detailed introduction to mission concepts and goals see [2,3,4].

Analogue mission scenarios: Two scenarios were planned and executed over three field deployments: (1) A robotic sample return mission to SPA; (2) A robotic precursor mission to SPA with a follow-on 7-day human sortie mission. Operations for each of these scenarios comprised two distinct groups: a field team at the deployment site and a Mission Control (MC), team based at the University of Western Ontario in London, ON.

Scenario 1. The first scenario was a purely robotic mission, such as the Moonrise mission proposed for the NASA New Frontiers call for missions[5]. This scenario was executed at the *Sudbury impact structure*, ON, Canada in the Spring of 2011 and is referred to as the Sudbury Lunar Analogue Mission (SLAM).

Scenario 2. Scenario 2 consisted of a robotic precursor mission to SPA to be followed, approximately 6 months later, by a human sortie mission. The precursor mission involved robotic surveying and prospecting of Sites of Interest (SOIs) in preparation for human field geology operations. The robot would then act as an astronaut assistant during the human sortie mission phase. We refer to these scenarios as 2A and 2B. These scenarios comprised the Kamestastin Research Analogue Site for Human exploration (KRASH) mission, which was executed over 2 field deployments. The robotic precursor phase took place in 2010 and the human sortie mission in 2011. Both were conducted at the *Mistastin Lake* (Kamestastin) *impact structure*, Labrador, Canada.

In addition to the CSA contract, our team also completed a fourth deployment in November 2011 - a short purely human scenario to the *Barringer impact structure*, *Arizona*, *USA*. This mission is referred to as the Barringer Lunar Analogue Mission (BLAM).

Results: *SLAM:* The deployment to the Sudbury impact structure (Scenario 1) was carried out over 2 weeks in June of 2011 at a single site just south of the city of Sudbury. UTIAS's ROC6 rover, aided by a field team, traveled 2,200 m on site, completed 43 command cycles instructed by Mission Control, and collected 17 core samples of which 10 were selected to be returned to 'Earth'. Details and results of the operational procedures are outlined in [6,7].

KRASH 2010: The first field deployment to the Mistastin Lake structure (Scenario 2A) was carried out over the course of 4 weeks from mid-August to mid-September 2010. Operations were carried out at 3 main sites, chosen by scientists who had not previously visited the site, through a rigorous site selection process using remote sensing data sets (detailed in [8]). Details of the field procedures and lessons learned from the precursor mission are outlined in [9].

KRASH 2011: The second deployment, a human-sortie mission to the Mistastin Lake impact structure (Scenario 2B) was carried out during mid-August to mid-September 2011. Operations were carried out at 2 main sites visited in 2010 and chosen based on precursor data generated during Scenario 2A [10, Fig. 1]. Each week represents a separate mission. In the first week, a team of 2 astronauts with a rover assistant completed 4 extravehicular activities (EVAs), identified numerous SOIs and collected 14 samples at Site 1 located on the crater rim. During week 2 the rover continued to the same SOIs to autonomously navigate to sites chosen by MC and then collected additional data, while the astronauts moved to Site 2, completing 4 astronaut-only EVAs and collecting 17 samples. Additional EVAs were planned but could not be completed due to severe weather conditions. The value of remote sensing data and precursor data to plan and execute follow-on human science and operations at Mistastin are detailed in [3, 11] and results of planned traverses and astronaut tracking techniques during real-time communications are detailed in [12].

BLAM: The fourth and final deployment, this time to Barringer crater, was completed over the course of 5 days in November of 2011 and successfully applied lessons learned from previous missions.

Conclusions: This analogue mission campaign demonstrated the value of conducting real, cutting edge science in parallel with developing operations – scientific results include the discovery and documentation of ejecta deposits [13], the novel discovery of melt-bearing impactite dykes within the central uplift at Mistastin [14,15], glass clast morphology showing evidence of variable timing, sites of incorporation, and emplacement in melt-bearing breccia [16], and field observations to support a large impact melt pond at Mistastin [17].

All four scenarios have advanced impact cratering geological knowledge and have aimed to improve lunar mapping methods, remote sensing analysis, site selection, visual and analytical instrumentation and sampling protocols as detailed in [18, 19, 20]. An evaluation of the results of the cooperative human-robotic exploration from scenario 2 is detailed in [21], and the architecture of Mission Control is detailed in [22, 23, 24]. Finally, an evaluation of real-time data management and recommendations for future ground stations is detailed in [25].

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