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A Mission Control Architecture for robotic lunar sample return as field tested in an analogue deployment to the sudbury impact structure

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Abstract

A Mission Control Architecture is presented for a Robotic Lunar Sample Return Mission which builds upon the experience of the landed missions of the NASA Mars Exploration Program. This architecture consists of four separate processes working in parallel at Mission Control and achieving buy-in for plans sequentially instead of simultaneously from all members of the team. These four

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processes were: science processing, science interpretation, planning and mission evaluation. science processing was responsible for creating products from data downlinked from the field and is organized by instrument. Science Interpretation was responsible for determining whether or not science goals are being met and what measurements need to be taken to satisfy these goals. The Planning process, responsible for scheduling and sequencing observations, and the Evaluation process that fostered inter-process communications, reporting and documentation assisted these processes. This organization is advantageous for its flexibility as shown by the ability of the structure to produce plans for the rover every two hours, for the rapidity with which Mission Control team members may be trained and for the relatively small size of each individual team. This architecture was tested in an analogue mission to the Sudbury impact structure from June 6–17, 2011. A rover was used which was capable of developing a network of locations that could be revisited using a teach and repeat method. This allowed the science team to process several different outcrops in parallel, downselecting at each stage to ensure that the samples selected for caching were the most representative of the site. Over the course of 10 days, 18 rock samples were collected from 5 different outcrops, 182 individual field activities – such as roving or acquiring an image mosaic or other data product – were completed within 43 command cycles, and the rover travelled over 2200 m. Data transfer from communications passes were filled to 74%. Sample triage was simulated to allow down-selection to 1 kg of material for return to Earth.

Keywords: Sample return; South Pole-Aitken Basin; Mission control; Analogue missions; Moon

1. Introduction

NASA and other space agencies have acknowledged the usefulness of analogue activities since the Apollo era to prepare for space missions (Deems and Baroff, 2008; Léveillé, 2009). Analogue missions can be broadly defined as an integrated set of space exploration activities, conducted by a team, at a site which simulates multiple environmental conditions of a planetary target and results in an understanding of system level interactions. Essentially Earth-based expeditions, with characteristics that are analogous to missions on the Moon, Mars, or other solar system bodies; an analogue missions allow technologies, day-to-day operations, scientific procedures, and exploration strategies to be safely tested in planetary-like operational environments (Osinski et al., 2006; NASA, 2011).

Activities encompassed within analogue missions include three different categories: scientific, technological, and operational (Deems and Baroff, 2008; Snook and Mendell, 2004). This paper focuses on the latter, and describes a Mission Control Architecture that was developed for a Robotic-Only Lunar Sample Return Mission. The simulation took place from June 6–17, 2011 and included a remote Mission Control team based at the University of Western Ontario. A rover with accompanying field team was also located ~380 km away at a site in the Sudbury impact structure. This accompanying field team was considered to be outside of the scenario; they did not include any members acting as astronauts within the simulation. The overall mission scenario is based on a robotic sample return mission from the Moon's South Pole Aitken (SPA) basin, similar to the MoonRise mission concept (Joliff et al., 2010).

The scientific context for this analogue mission was the investigation of impactites (i.e., rocks affected by impact events), specifically impact melt rocks. Returned impact melt samples from the SPA would help geologists decipher the bombardment history of the inner solar system, and understand impact process on planetary scales; both key scientific goals defined by the National Research Council (NRC) recommendations for lunar exploration (NRC, 2007) and ranked highly within the recent planetary decadal survey (Squyres et al., 2011).

Within this context, key objectives of this analogue mission were:

(1) Develop and refine techniques/protocols for identifying, mapping, and sampling impactites.
(2) Determine if the navigation considered in the analogous space mission can be performed accurately and efficiently without dependence on satellite-based global positioning for localization.
(3) Test the communication architecture and the performance of mission control within the scenario.

Objective (1) is described in greater detail in Marion et al. (2011) and the navigation scheme that was used, objective (2), is discussed more fully in Furgale and Barfoot (2010). As such, this paper will focus on objective (3) in addition to providing the overall context of the Mission Control Architecture that was used to evaluate all objectives. Section 2 will discuss the analogous scenario used to place this activity in context. Section 3 will discuss the overall architecture itself and Section 4 will discuss the performance of this architecture. Implications and lessons learned are discussed in Section 5.

2. Scenario

The overall mission scenario is based around a robotic mission for sample return from the Moon's South Pole Aitken Basin on the lunar far side. This is similar to the MoonRise mission concept (Joliff et al., 2010) except enhanced with roving capabilities. In the scenario, a rover and an orbiter designed for both mapping and communications are launched from Earth (spacecraft currently in orbit about the Moon could also be used in this capacity). The rover lands, egresses from a lander and may travel about the landing site to characterize the area and to select the best samples for return to the earth. Once these samples have been identified, rock cores are obtained and loaded into an ascent vehicle back at the lander. The rover and lander are supported by the mapping orbiter whose task is to provide relay communications with the Earth and, following completion of the sample return mission, to perform mapping of the Moon. The specifics of this mapping activity are beyond the scope of this paper, however, the key point is that this scenario posits a non-dedicated orbiter which could go onto perform other activities (most likely mapping) once the ascent vehicle has returned to Earth.

2.1. Mapping orbiter and communications

Only one relay spacecraft is assumed to support the spacecraft. It is further assumed that data relay is not the only responsibility of this support vehicle. However, during sample acquisition, this orbiter will occupy a frozen orbit to provide maximum data relay to the surface. This ensures that there is both very little fuel consumption, but more importantly, that the orbit does not process with respect to the longitude of the landed spacecraft. A good analogue to this situation is the Lunar Reconnaissance Orbiter (LRO) which is able to transition easily between a frozen polar orbit with a 2-h period and a processing polar orbit suitable for mapping (Chin et al., 2007; Beckman, 2006). As such, an LRO-like craft is assumed for the orbiter.

The frozen orbit of this Mapping Orbiter drives the communications between the ground and the rover on the lunar far side. Thus, the 2-h orbital period defines the operational cycle, termed a “Command Cycle”, to be employed in Mission Control. Communications between the relay vehicle and Mission Control are only possible when it is in view of the Earth over the near side of the Moon. Therefore new data can only arrive once per two hour cycle, and the rover can only be commanded once per two hour cycle. Since the South Pole-Aitken Basin is at southerly latitude, we have assumed little lag between this commanding Drop-Dead Uplink Time (DDULT) and the beginning of task execution. Furthermore, for simplicity, we have assumed that the lander may communicate with the orbiter at any time while the orbiter is over the far side and that mission control can communicate with the orbiter whenever the orbiter is over the near side. Since the altitude of a 2-h orbit about the moon is low, between 120 and 130 km above the surface, there is no time when the orbiter would be in contact with both Mission Control and the centre of the SPA. This organization is also easier for the field team to implement in the analogous situation on the Earth. The analogous communications scheme is shown schematically in Fig. 1.

Serving as an analogue for the Mapping Orbiter is the Anik F-2 geostationary satellite which is accessed by a satellite phone data link. Given low data-transmission rates from Anik that are than what would be expected for a dedicated Deep Space Network (DSN) link with the Moon, the field team was permitted to continuously downlink data as it was obtained. This data was then embargoed until the Mapping Orbiter would have been visible to the Earth. The total amount of data permitted during any one downlink was up to 480 Mb which represents a time requirement of only a few seconds at currently achievable downlink rates from the Moon of up to 100 Mb s^{-1} (Everett et al., 2008; Tooley, 2006). This is important to simplify the handling of data which was released immediately to the science team upon the first visibility of the Mapping Orbiter. Thus, 480 Mb was the limit of the amount of data which could be collected within a single Command Cycle and this data volume was phased and monitored accordingly by Mission Control. The total amount listed here is comparable to the design data volume for LRO of 572 Mb over a single day (Tooley, 2006).

2.2. Surface rover and simulated exploration system

The parameters for the rover were set by the abilities of the ROC-6 platform provided by the University of Toronto Institute for Aerospace Studies (Barfoot et al., 2010) and shown in Fig. 2. The major factor affecting Mission Control from this platform is the time required for traverses to take place. Traverses using this rover are an order of magnitude faster than current space-qualified hardware, 0.3 ms^{-1} for the ROC-6 (Barfoot et al., 2010) compared to 0.025 ms^{-1} for the Mars Science Laboratory (MSL, 2010) over level terrain. However, this simply means that the 2-week analogue deployment demonstrates a compressed version of a longer sample return mission. Such an extended mission might operate 24 h a day and seven days per week and potentially over several lunar diurnal cycles.

While traversing to a new location, the rover employs a path planner which performs obstacle avoidance based upon navigational sensors and a LiDAR base map of the surrounding terrain (Furgale and Barfoot, 2010). The path planner may make several attempts at achieving a waypoint. As such, it was necessary to book keep time for this activity in the field with a 30-min limit (Furgale and Barfoot, 2010). However, this limit was not required when returning to previously visited waypoints, as the rover could autonomously navigate to a previously visited waypoint directly (Furgale and Barfoot, 2010). Thus, one of the activities with the ROC-6 was to build up a network of sites of interest to enable parallel investigations at several sites. This was very helpful in reducing the number of forward dependencies and allowing the Mission Control Team to plot out activities well ahead of time.

An additional constraint of the rover is its ability to carry instruments. Details of each instrument will be described in Section 2.3. Not all instruments could be accommodated on the rover at any one time. Furthermore, one instrument, the Ground-Penetrating Radar (GPR) encumbered the rover by preventing backward movement

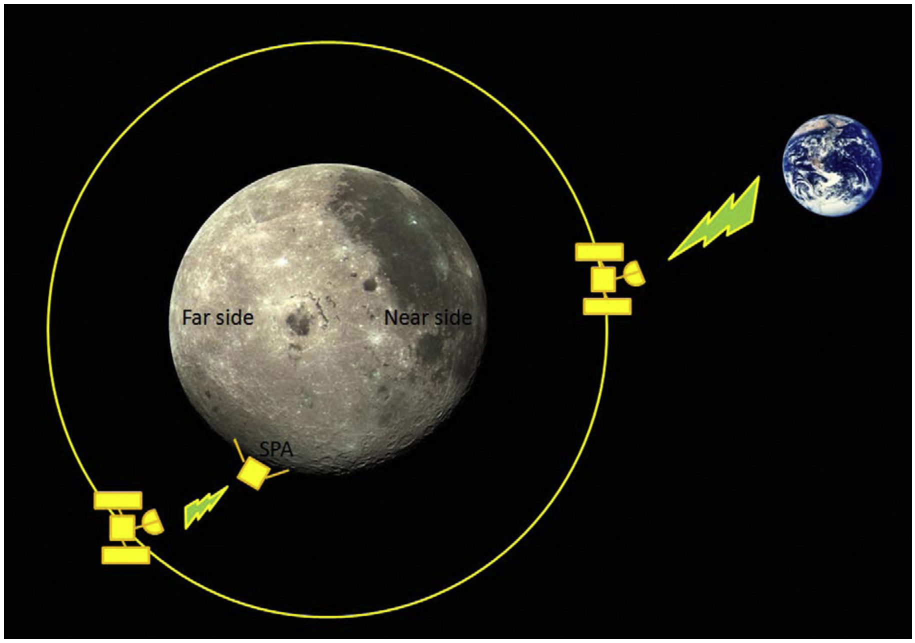


Fig. 1. Cartoon of the communications scenario which drives the mission control cadence. The mapping orbiter shown has an orbital period of 2 h and alternates between contact with Earth and contact with the rover located on the lunar far side in the South Pole-Aitken (SPA) Basin. Note that this Fig. is diagrammatic only and is not shown to scale.

Fig. 2. The ROC-6 rover showing instrumentation configurations. (MAIN) The GigaPan camera mount is shown on a mast above the middle rover segment with the C2SM camera head shown on the rightmost segment and the GPR to the left of the leftmost rover segment. In the background the "Guinevere" outcrop (see Fig. 10) can be seen. (INSET) During the second week the C2SM was replaced with an ILRIS LiDAR, shown in yellow, and the GPR was removed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

while attached. As such, different payloads were assumed to be functional during each of the two weeks of the deployment. During the first week, three instruments were mounted on the rover: the GigaPan Camera, GPR and an MDA Crime Scene Modeller (C2SM). While the LiDAR was not mounted on the rover during week 1, a single LiDAR scan from the centre of the landing site was made available to the team, as if the LiDAR system had been mounted on the Lander/Ascent Vehicle, or alternatively, had failed just after landing. This scan was necessary for the rover path planning algorithm to be effective. During the second week, the GPR was removed and the C2SM was replaced with an ILRIS LiDAR. During both weeks two contact instruments were used: a Raman Spectrometer and the Coring And Sampling Subsystem (CASS) that acquired samples. Field personnel operated the contact instruments independently of the rover, however, the use of these instruments was restricted to targets within a range of 1–2.5 m from the rover at the time of use.

Power was not considered to be a limiting factor for the rover and therefore there was no battery management performed. Furthermore, since the equipment used in our scenario was off the shelf, the power profile of these instruments is not representative of instruments designed for flight. As such, the ROC-6 was equipped with a gas generator to recharge batteries and suitable for powering a full day of traversing and instrument use. While this set-up does not preclude any specific charging method, such as solar power, this device is most analogous to a Radioactive Thermoelectric Generator (RTG) of the type typically used during spacecraft missions. However, the power output to weight ratio is significantly higher. For MSL, roving is limited by the output of the onboard RTG and thus power constraints will likely play a large role in any actual mission.

Likewise, the rover was equipped with several hundred GB of onboard memory which precluded the requirement to perform memory management over two weeks of operations. Furthermore, the relatively large downlink capability of the Orbiter link (see Section 2.1) and the relatively low data-gathering capabilities of the instruments (see Section 2.3) meant that very little management of onboard data was required. Since it was rare for a Command Cycle to acquire more data than could be fit into a single downlink, complicated prioritization schemes were not simulated.

2.3. Instruments

A suite of seven instruments were sought for use with the rover. These were the GigaPan, LiDAR, C2SM, GPR, a Raman Spectrometer, an X-ray Fluorescence (XRF) Spectrometer and the CASS device. The first four of these were rover-mounted while the last three were contact instruments. Unfortunately, the XRF failed prior to use and a replacement was unavailable for the deployment. Each of these instruments is discussed in turn along with their capabilities and constraints.

First, an imaging system consisting of a DSLR Camera mounted on a GigaPan frame, to allow for the creation of mosaics, was located on a mast at the centre of the rover. This GigaPan instrument allowed us to take full-colour photographs at three different zoom settings (55, 35 and 18 mm) and three different resolutions (presets compressing to approximately 8, 20 and 28 Mb per image, with margin). Thus, this instrument enabled many of our Science activities by providing the context for other data sets and rudimentary spectral and textural information about the terrain and individual targets. Generally, panoramas composed of multiple images were acquired which required Mission Control to accurately anticipate the pointing of the rover at a waypoint, point the camera relative to the rover, and to stitch together the images returned from the field.

LiDAR and C2SM each gave ranging data for contact measurement locations as well as shape and texture information. In addition to their scientific utility, a close-in scan from one of these instruments was required by the flight rules before a contact instrument could be safely positioned for use in order to obtain high-resolution 3-dimensional positioning. LiDAR scans required up to 50 Mb per $40° \times 40°$ segment. Thus, a full 360° scan in azimuth typically required close to the whole 480 Mb Command Cycle downlink for 10 segments, allowing for overlap. The C2SM had much more flexibility in terms of modes. 120°-wide swaths of the surface between 2 and 8 m from the rover could be acquired for close to 60 Mb. C2SM also possessed a high-resolution imager which was useful for documenting operations performed with touch instruments. Each of these images was approximately 72 Mb in size. For each of these instruments, both pointing and stitching was much easier than with GigaPan, reducing the workload at Mission Control.

In contrast to the rover-mounted instruments, the contact instruments were pointed using a different method. In order to interface with the field team, images annotated with small boxes were uploaded to the field to select points. However, for each of these, the ability of the instrument to contact that location was assessed with C2SM or LiDAR to ensure that an XYZ coordinate could be specified for a robot arm. Raman data was intended to describe mineralogy while the XRF instrument, had it been available, would have given geochemical data. The goal of the mission was to characterize the site (i.e., document variations between rock types) and not prospect for a particular type of mineralogy or geochemistry. These instruments were very helpful in performing the final sample triage at the end of the mission to establish that different rock types were being sampled and to select the least altered samples. Compared to the three rover-mounted instruments, neither of these instruments generated a significant amount of data volume with neither able to produce a single Mb even if operated over an entire command cycle.

2.4. Exploration strategy: large scale to small scale in parallel

The final scenario-specific constraints on the Mission Control Architecture are given by the high-level exploration strategy for the landing site. This strategy is set out in the ILSR proposal (Marion et al., 2011; Mader et al., 2011) and is best expressed as a flow-chart (Fig. 3). This

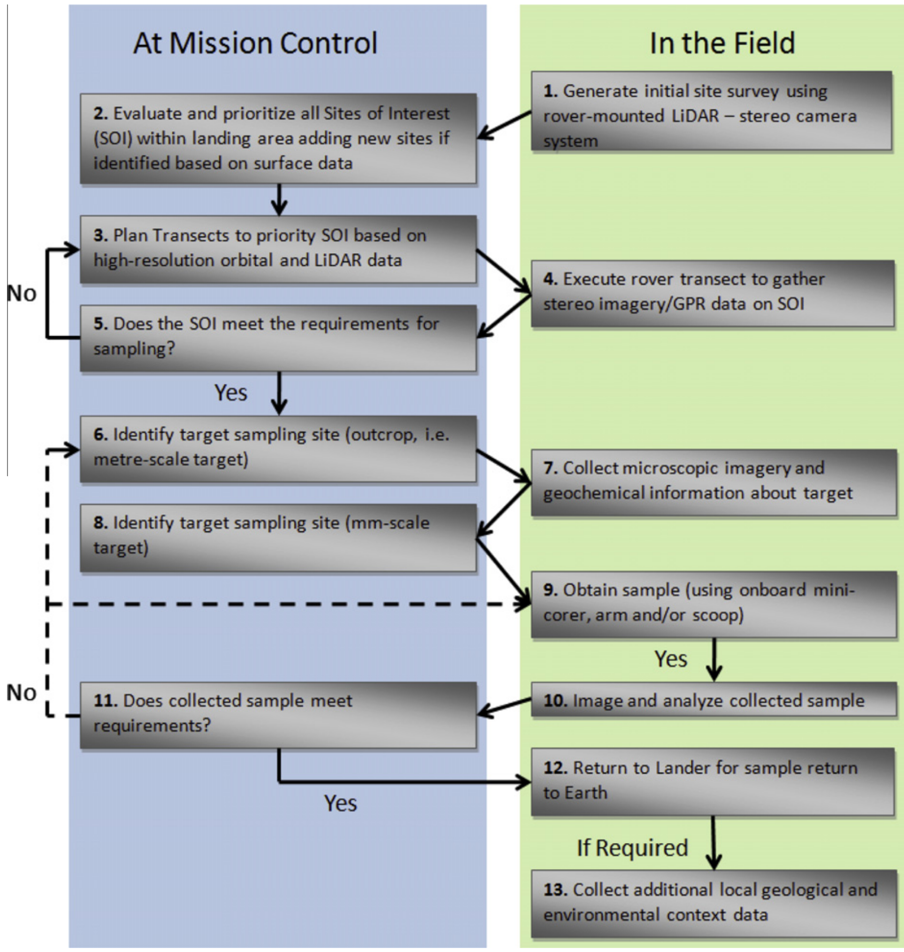


Fig. 3. The sampling flowchart for the ILSR mission following landing, after Marion et al. (2011). While this flowchart is written in the context of the investigation of a single site of interest (SOI) to acquire a single sample, the ROC-6 roving network architecture allows this flowchart to be followed for several sites in parallel.

strategy describes an investigation which begins at a large scale and moves towards a progressively finer scale, terminating with sampling and caching for return to Earth.

The sampling strategy is written in the context of a single, isolated, sampling site. However, the network building capability of the rover (Section 2.2 – the ability of the rover to autonomously navigate to a previously visited site) suggests that several sites could be examined in parallel at different scales during a single command cycle. This would allow Mission Control to down-select to the best targets at each stage. For instance, there might be several very interesting targets visible from the landing site. Traverses and higher resolution imagery might next reveal which of these are most interesting from the perspective of sampling. At any given waypoint/site of interest, larger scale imagery can be collected as well, resulting in the discovery of new larger-scale sampling sites. This means that the list of most interesting long, medium and short-range targets will evolve over time. As such, more samples are likely to be collected than can be returned to Earth. This necessitates a sample triage operation prior to the departure of the ascent vehicle. A similar operation may be performed for future Mars Caching rovers. Previous proposals for a 2018 combined-NASA/ESA mission (Exo-Mars/MAX-C) have listed a capacity to collect up to 38 samples (Salvo and Elfving, 2010), but the ability to cache only 20 for return to Earth (Zacny et al., 2011). The total permissible return is analogous to the proposed MoonRise mission for which a total of 1 kg is permitted (Joliff et al., 2010).

The parallel strategy is effective for Mission Control as it reduces forward dependencies between subsequent command cycles and allows better use of each cycle. Despite this, mission safety considerations likely require some time spent in a serial mode at the start of the mission to ensure that at least one sample is acquired. This initial serial mode was employed in our scenario. Following the lifting of this constraint with the acquisition and caching of our first sample, the sampling objective may be expanded into a search for the best samples within the constraints of the return/ascent vehicle and the range of the rover. Depending on the specific mission risk posture, this serial mode may extend to more than one sample and could potentially encompass all samples, in the most extreme case.

2.5. In-scenario goals

In addition to the goals of the analogue test described in the introduction, there were several goals, in-scenario, which correspond to expected goals for an actual mission. These were:

(1) Characterize the geology of the landing site, in particular searching for evidence of impact melt.
(2) During week one: at least one sample must be acquired and cached. The acquisition of this sample must follow the flowchart of Fig. 3.
(3) During week two: the rover must expand the LiDAR map at least once by roving more than 10 m and acquiring a second LiDAR scan.

3. Mission Control Architecture

3.1. Heritage

As motivated by Yingst et al. (2011), the Mission Control Architecture was designed based upon the Mars Exploration Program. Elements of Mission Control Operations from MER, Phoenix and MSL were adapted to the scenario described in Section 2. Furthermore, due to staffing limitations, there was substantial motivation to find efficiencies within each sub-process making up the overall architecture of Mission Control. Thus, the architecture which is described in this section can be considered as a prototype for missions for which low staffing is desired. This might include private lunar exploration where focused goals and a small team would be implemented to give a cost-effective posture. Conversely, this architecture can also be considered applicable to larger agency-run missions for whom it is desirable to free up as much of the science team as possible from the demands of a 2-h command cycle of operations to focus on data analysis.

Given that the ROC-6 rover is designed to build up a network of traversable points, the most similar previous mission is the Phoenix Mission. For Phoenix, any new surface contact activity using the robot arm was a time–costly activity with some positioning uncertainty. However, previous activities and locations could be easily repeated or revisited (Arvidson et al., 2009). Similarly, building up a network through rover exploration is a relatively time–costly task which carries positioning and orientation uncertainty, but returns to previous waypoints are simple and well-understood (Furgale and Barfoot, 2010). This enables the mission described in this paper to undertake a parallel investigation strategy, as described in Section 2.4, as opposed to the more serial approach of a rover with a final destination, such as MER or MSL. This structure is appropriate for a sample return/sample caching mission in which the rover is ultimately tied to a central point to which samples must be returned.

3.2. Processes

There are a total of six separate processes which were present during the Phoenix Mission, three of which were explicitly described by the Operations Concept Document (Eagles et al., 2008) and in descriptions of the surface mission operations process (Bass and Talley, 2008). These are: (1) Tactical Planning and its low-level follow-on counterpart, (2) sequencing as well as a separate, (3) strategic planning process. Three other processes took place, but were beyond the scope of that document. These were (4) science data processing, (5) science interpretation and (6) programatic mission evaluation. The processing of science data downlinked from Phoenix to create data products useful for science was a responsibility that fell upon each instrument team. These teams, in turn, interfaced with the Tactical and Strategic Planning Processes through an Instrument Downlink Engineer (IDE). The interpretation of these data products fell upon the Science Theme Groups which interfaced with the Tactical and Strategic Planning Processes through Science Theme Group Leads (STGLs). Finally, the process was monitored and tweaked by representatives from NASA, as required. This monitoring and modification process is effectively one of mission evaluation.

Since the size, experience and time for training were all limited for the volunteer team available for ILSR Mission Control, it was necessary to reorganize these processes. However, since all instruments used were off-the shelf and easily understood by all, it was unnecessary to form explicit instrument teams. Thus, functions of science processing, science interpretation and mission evaluation were left intact but were each achieved with a single team rather than with several teams. A new process named Planning was created which took on many of the formal responsibilities of Strategic, Tactical and Sequencing. However, certain responsibilities of these three processes were downloaded to the other process teams, as appropriate. Descriptions of each of the four process used by ILSR are provided below. The overall hierarchy of this architecture is shown in Fig. 4.

3.2.1. Planning

Planning chiefly took on three tasks. The first was determining whether observations prioritized by the Science Processes were achievable by the overall landed system and what the associated resource cost of making each observation would be. Secondly, Planning was responsible for scheduling these observations in such a way that science-return from the field was maximized without violating the flight rules or constraints of the mission. Finally, Planning was responsible for translating each requested science observation into individual commanded sequences for transmission to the field. In this context, a sequence is a specific low-level instruction to perform a task. It is written in plain English, but follows a fixed convention and

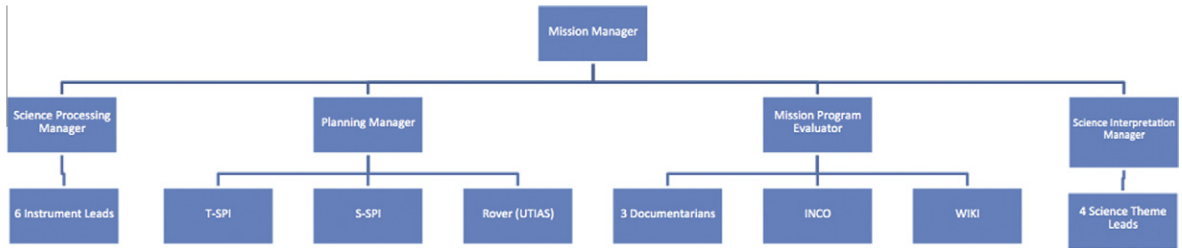


Fig. 4. Hierarchical organization of the ILSR Sudbury Deployment. The Mission Manager bears responsibility for allocating resources between each of the four processes: science processing, planning, evaluation and science interpretation. The process leaders, the mission manager and several external participants make up the leadership council.

explicitly defines all parameters. Improperly written sequences were not executable by the field team.

In order to accomplish these tasks, the Planning Team was composed of six functional roles. These were: (1) a rover path planner who planned traverses and spoke to the capabilities of the rover, (2) a sequencer to perform the translation of activities into field-readable instructions, (3) a science planner/integrator (SPI) responsible for monitoring data budgets, instrument capabilities and scheduling in the short term, (4) a science planner/integrator (SPI) responsible for monitoring data budgets, instrument capabilities and scheduling in the long term, past the end of the current day, (5) the Mission Manager, to monitor the flight rules and their application to an individual Command Cycle's plan, and finally (6) the Planning Manager who assumes responsibility and leadership for the Planning Process and allocates personnel as required to meet the Drop-Dead Uplink Times (DDULTs) when instructions are due at the field.

Since the short-term SPI in this process concentrated on the next Command Cycle, he or she was usually termed the Tactical or "T-SPI" to distinguish them from other team members performing similar tasks. The longer-term SPI was distinguished as the Strategic or "S-SPI". While the Mission Manager was part of the process, they also have authority over the entirety of Mission Control and were therefore also responsible for issuing "green cards" as needed by the Planning process. A "green card" occurs when the team requests an activity which the field is unable to perform in an analogous way to the real scenario, but which would be an approved activity in a real mission under the scenario described in Section 2. A good example of this is sample collection. It was not possible to mount a robot arm and coring device onto the rover directly. Instead, a field team member was sent to collect cores with a portable device. It was not possible to pre-plan for every contingency; therefore determining where such green cards were required was one of the outputs of the analog mission process, though beyond the scope of this paper.

Aside from the direct integration of the Phoenix Sequencing and Tactical processes within Planning, the largest change is the absence of specific team members within this process who were responsible for speaking to instrument capabilities and to science value of the observations. This expertise was available from science processing (instrument leads) and science interpretation (science theme leads) on an as-needed basis. The reason for segregating these groups was a desire not to duplicate expertise. Due to the limited staffing available, it proved unworkable to staff these instrument and science roles in multiple processes. However, this segregation had an advantage; the increased flexibility of a smaller planning team allowed the team to more easily achieve appropriate buy-in from all parties within Planning on the scale of the two-hour command cycle and to re-task as necessary, depending on the specific activities to be performed. This increased flexibility was crucial as four command cycles were commanded per daily shift (8 h) instead of the single Phoenix command cycle per sol (24.7 h).

3.2.2. Science processing

Science processing contains the instrument expertise and provides bookends to the analysis process. At the front end, when data arrives at Mission Control, it is this process which converts the data into useable products for scientific analysis. Similarly, once interpretation and prioritization of targets of interest and observations takes place, it is science processing which determines which instruments can most effectively gather the science requested and whether that instrument package can achieve the observations requested. As such, science processing works very closely with science interpretation and for certain tasks many individuals will travel back and forth between the two groups when work permitted. However, in terms of the functioning of Mission Control there is one major difference; science processing remains on the 2-h Command Cycle and is responsible for forwarding science objectives and observations to Planning whereas Science Interpretation does not follow the 2-h cycle (see Section 3.3.1 and Fig. 5 for more details on the relationship between the two science groups).

Within this process, a representative for each instrument was designated and, where practical, an additional member of the science team was assigned to double check the work that was done. This doubling up was typically possible since only a small subset of the instruments were used in any one command cycle. In addition to these roles, there was also a liaison between the science processing and

Fig. 5. Process flow for the ILSR Sudbury Deployment. Each task is color-coded by process/location. The field is blue, science processing is green, science interpretation is gold, planning is red and mission evaluation is grey. This process must be followed for each activity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

planning. This prevented disruption of the workflow in either room, helped science processing to formulate instructions in an effective way and gave planning a representative from science processing to query about the details of the requests. This liaison role was filled by a person who was familiar with both processes (typically trained as a SPI). An important factor in relaying requests from Science was that the "Instructions" were delivered face-to-face. This was previously found to be effective within the MER program (Parke and Mishkin, 2005). To organize the work of the science processing process including delegation of human and computer resources and to ensure that deliverables to science interpretation and planning were delivered on time, there was also a science processing manager.

Thus, science processing fulfills some of the responsibilities of the Phoenix Tactical Process with regards to instrument buy-in on observations and also performs the processing of those observations.

3.2.3. Science Interpretation

The main purpose of Science Interpretation was to focus on the long term science goals of the mission which cut across the boundaries of instruments. This included analysis of orbital data sets, integration of different datasets and prioritization of objectives and potential observations. Thus, Science Interpretation fulfills some of the responsibilities of the Phoenix Strategic Process with regards to formulating a long-term plan. Since these overall interpretations depend on the results from multiple command cycles, science interpretation does not need to keep to the 2-h command cycle, though new data was examined as it became available from science processing. The science interpretation team worked in the same room as the science processing team because this allowed science processing team members to contribute to Science Interpretation when they were done with their processing duties.

Like the other processes, Science Interpretation has a manager who oversees Science Leads, each of which is responsible for a science theme. If knowledge along any one of these themes is required by planning or science processing, this expertise is available from this process. Given the nature of its work, science interpretation is otherwise permitted to define their goals and work schedule which evolves along with the data that is received at mission control.

3.2.4. Mission evaluation

Mission evaluation is concerned with the process itself. The goal of this process is to improve inter-process communications and to document how and why decisions were made. It is useful for those within the process to understand why a previous decision was made so that errors are not repeated. In addition, the mission evaluation process provides feedback to a leadership council (see Section 3.2.5) which determines if changes need to be made to the overall process during the analogue mission itself on a day-to-day basis. External to the scope of the analogue test, mission evaluation also collects information for post-mission analysis, documentation and reporting.

This process is headed by a Mission Evaluator who is assisted by documentarians which are embedded in each process. There was also a member of this team (hereafter referred to as WIKI) who kept the internal information distribution system up to date and another who monitored incoming data from the field (hereafter referred to as INCO) and advised the science processing team on its availability.

3.2.5. Leadership council

The senior leadership of the project was collected together into a small group named the leadership council which met at the beginning and end of each day and whenever necessary within a day. Membership on this council was limited to the leaders of each main mission control process, the designers of the Mission Control Architecture, the Mission Manager and Field Site Manager. The Project Principal Investigator (Gordon Osinski) and Chief Engineer (Tim Barfoot) were invited to attend, but their presence was not critical to the functioning of the group. The Leadership Council had the role, in essence, of managing the mission simulation, and ensuring that the goals of the analogue project were being met by the simulation planned or running, and as such acted external to the scenario. This included setting or adjusting flight rules, reacting to equipment difficulties and external events with implications to the scenario, and deciding which aspects of an activity would be simulated or excepted from the scenario (‘green cards’). In this sense, the Council operated primarily outside the simulation.

Occasionally, where events in-scenario warranted, the same personnel would meet during simulation time to ensure consistency of planning and awareness across all mission processes. These in-scenario meetings can be seen as special summits of process leaders to guide the mission, as representatives of the various ‘departments’ in mission control. it was the responsibility of each process leader to inform those team members located within their processes about decisions made during the leadership councils which would impact the functioning of their process.

3.3. Process flow and meetings

3.3.1. Organization

A hierarchical chart of the organizational relationships between the four processes and the roles described above is shown in Fig. 4. The ultimate responsibility for allocating resources across the mission belongs to the mission manager. There is also a leadership council made up of the process leaders and other senior members of the team who advised on decisions (see Section 3.2.5). Within each process, managers had the ability to reassign personnel in real time as they thought best.

3.3.2. Process flow and boundaries between processes

The overall process flow for information is shown in Fig. 5. Every two hours, the mission control team executes this cycle once moving from the receipt of down-linked data around to the sequencing of new instructions for the field. Examination of the boundaries between different processes reveals that while Planning is distinct from the two science processes, the precise integration of the two science processes can be nebulous. In practice, the boundaries between science processing and Science Interpretation may be different for different teams, the largest difference being that one is tied explicitly to the command cycle (processing) while the other (interpretation) may provide their inputs at any time. As such, even though it is a distinct process, science interpretation acts as a sub-process of science processing from the perspective of the information process flow.

The boundary between the science processes and the planning process is one of the most important in the entire process flow. The ideal case is the one in which work is split equitably between both teams. Instructions from Science must clearly express the science goals behind each observation or Planning will find it difficult to manage tradeoffs if there are insufficient resources. Furthermore, there will be a tendency of Science to attempt to present instructions to planning at the level of individual sequences. Likewise, there will be a tendency for planning to anticipate Science Requests and schedule activities which have not had buy-in from the entire team. Both of these should be avoided. This is where the science-planning liaison is most valuable as this role fosters efficient communications between both processes (for an additional comment about this boundary, see Section 5.7).

3.3.3. Meetings, timing of data uplink/downlink and the command cycle

The process flow is advanced through meetings whose timing is defined by the series of command cycles which take place throughout the day. The initial configuration of this meeting cycle is presented as Fig. 6. Driving this cycle of meetings is the command cycle. Each command cycle is two hours in length with the exception of the first and final command cycles of the day. These have been lengthened to allow the rover and field team to perform exploration manoeuvres and other testing without requiring Mission Control staffing to be extended. If the mission were real, it is unlikely that the overnight cycle would be blank. Instead, it is expected that Mission Control would support continuous 2-h cycles over the length of the mission.

Based on Fig. 6, each cycle may be divided into two parts. While both hours are commanded in one uplink, downlink from the field occurs at the end of the first hour. The reason for this is that mission control must command activities to be performed both during the one hour when the mapping orbiter is over the far side as well as for the one hour during which the mapping orbiter is over the near side. However, in our scenario, it is only possible for the

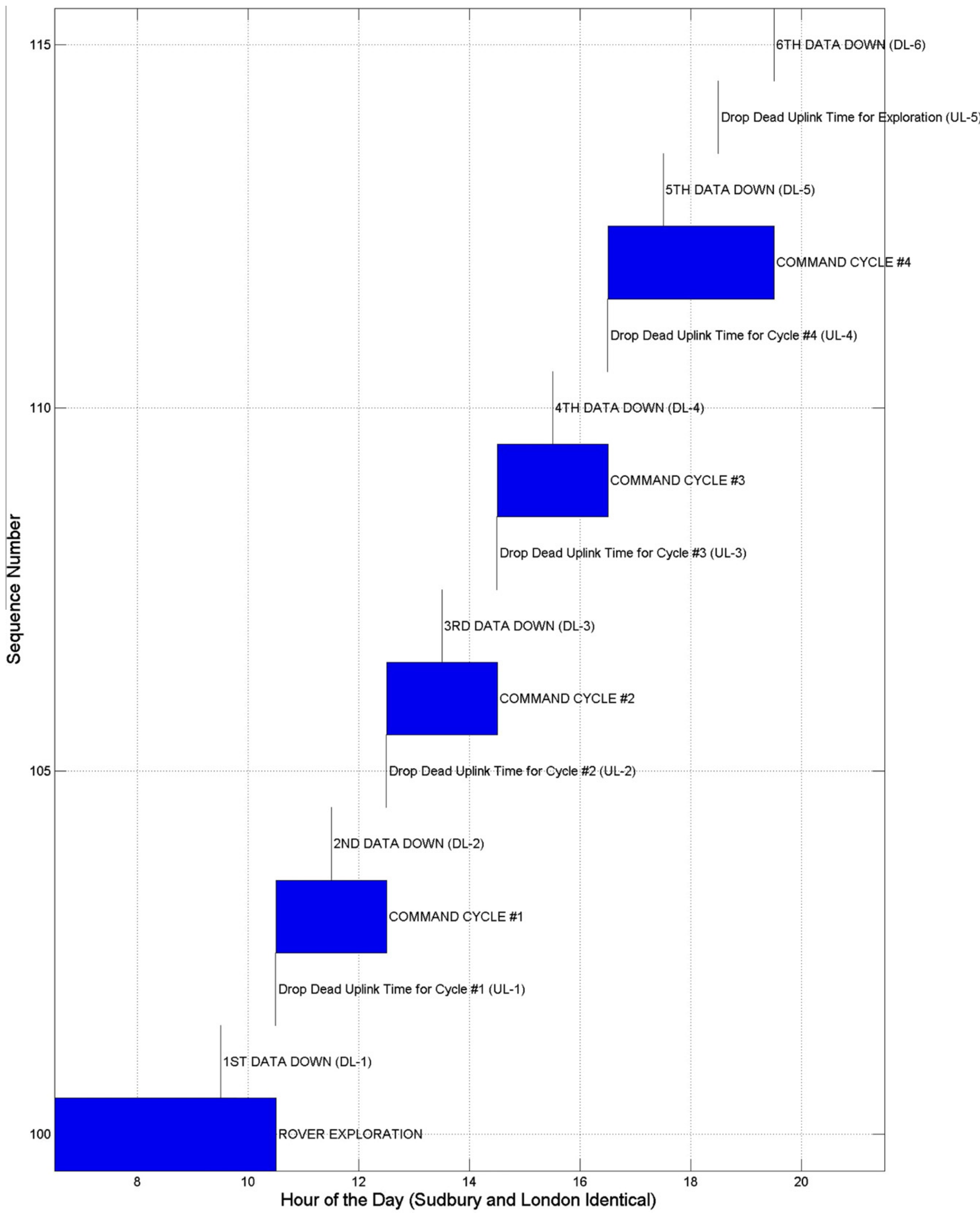


Fig. 6. The command cycles simulated by the ILSR Sudbury Deployment. Each cycle is two hours with the exception of the cycles at the start and end of the day. These have been lengthened to allow the field team flexibility in scheduling tasks unrelated to the mission. Data downlink from both is equivalent to the other cycles. Due to constraints in the field, command cycle #4 was shortened and rover exploration was dropped.

orbiter to communicate with the lander while the orbiter is over the far side. Thus at the end of the first hour, communications are cut off between the lander and the orbiter and opened between the orbiter and mission control.

Thus data only comes in from the first hour of that command cycle. The second hour's worth of data will be delivered in the next command cycle. While the orbiter is behind the moon during the first hour after uplink, mission control has a down hour. during this hour, science and planning may catch up on tasks or documentation from the previous hour or may prepare for the next data downlink. These are also the times when meetings are scheduled that require the attention of all. While the specific meetings used may vary from day to day at the discretion of the Mission Manager, the all-hands meetings could include a Kickoff and Briefing to start the day, a long term planning meeting to look several days out, a Midpoint Meeting to catch any errors before they propagate, a conference-style science team meeting, a strategic meeting for the next day and a Debrief of the Day's activities. No further formal meetings are required for the Science Processes. However, the planning process will likely wish to review the upcoming day's plans in detail. Further, it makes sense for the Leadership Council to meet twice a day to ensure that any changes to the mission, payload or flight rules are understood.

During the hour between the receipt of data downlink and the uplinking of new commands both rooms are busy by necessity. Science processing immediately begins processing the data with a mind towards any data that is required for planning. If there are direct forward dependencies between two command cycles, a quick turnaround is required by science processing. 30 min prior to the DDULT for the next command cycle, Science must have any requests that change the plan delivered to planning. At this point, planning begins their Tactical Meeting in which tasks are assigned that result in instructions relayed to the field. The deadline for the Planning team is strict and is set by the orbital mechanics of the mapping orbiter relay.

All of these meetings over the course of a day are shown in Fig. 7. In this table, the timing of each meeting is shown along with the timing of process shifts and field shifts. Data downlinks are indicated by yellow triangles and command uplinks are indicated by blue triangles.

3.4. Comparison with other similar analogue deployments

Other analogue missions, conducted by NASA, have also simulated robotic lunar surface operations using a remote mission control team, primarily through the desert research and technology studies (DRATS) program (e.g., Fong et al., 2010). These studies applied a hybrid of Apollo, Space Shuttle, Space Station, and MER operational concepts (Yingst et al., 2011; Fong et al., 2010). Building on these studies we also incorporated elements from Phoenix and MSL (see Section 3.1).

There are several key distinctions between the Sudbury analogue mission and previous robotic analogue missions conducting by other research groups, including:

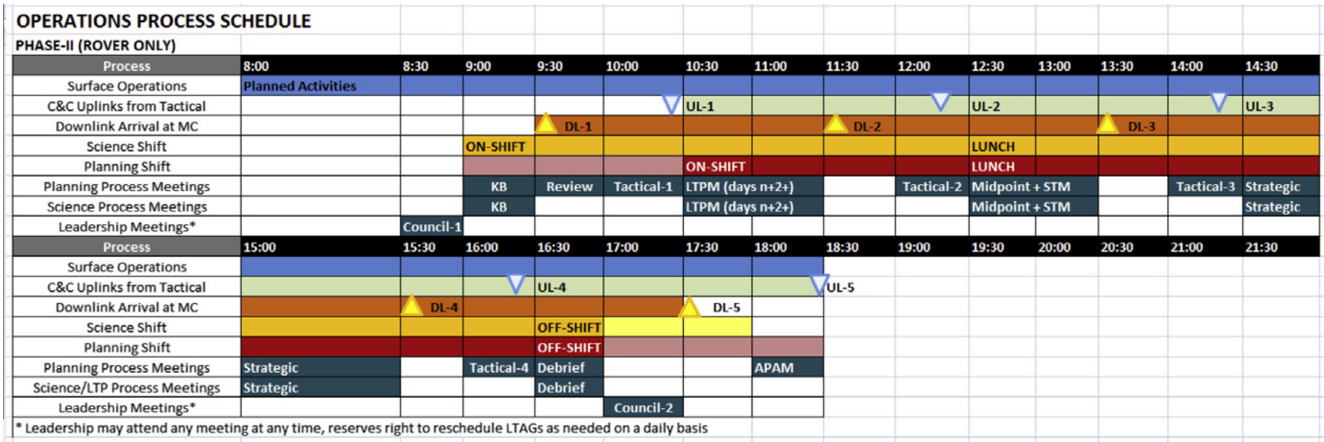
(1) The ROC-6 used a teach-and-repeat system (Furgale and Barfoot, 2010) which effectively allowed a branching network of paths to be developed in which the rover could autonomously returned to any point along the path. This ability enabled exploration at multiple scales in parallel during a single command cycle. This approach is fundamentally different from a MER and Apollo style of exploration in which previous field sites were not revisited, and exploration progressed in a serial fashion.
(2) We did not use global positioning systems (GPS) capabilities, Google Earth or local maps for rover navigation within the landing site. Instead, the rover used the teach-and-repeat system to autonomously navigate the field site and visual odometry was used to produce a plan (overhead) view of the rover's tracks overlaid on the LiDAR map (Fig. 10). For interpretation, this rover track was overlaid on QuickBird satellite images using ArcMap, a geographical information system (GIS) software (Fig. 10). Google Earth was also used to locate and provide a view of the broad landing site. Locations were georeferenced manually by Mission Control team members through visual comparison between surface imagery collected by the rover with orbital data sets. However, due to the reconfiguration of the landing site between acquisition of orbital imaging sets and the analogue mission there were disagreements between the visual odometry and the orbital data sets.
(3) Our analogue mission operated on a strict 2 h command cycle. Other robotic lunar analogue missions have tested communication schemes involving realtime communications between the rover and Mission Control, which were at different sites (Fong et al., 2010). In addition, some DRATS human-robotic analogue missions have also tested twice a day (NASA, 2011) communication schemes.

4. Results from the sudbury deployment

This section describes, in brief, the performance of the team described in Section 3 to carry out the scenario described in Section 2. Where lessons learned may be drawn, these have been highlighted.

4.1. Evolution of the operations architecture

The process and division of work remained relatively stable during the course of all 10 days of the deployment. The emergence of the Science-Planning liaison on the third day of the deployment was the most significant change and helped considerably with managing the hand-off of work between these two processes. Aside from this, all changes to roles were minor and by the end of the two weeks all



MEETINGS	Time	Description
Leadership Council-1	8:45	Project Management tags up - High Level Meeting
Kickoff and Briefing (KB)	9:00	Start of the day roll call, brief description of day's activities by MM
Review	9:00	Planning looks over the entire day's tactical plan w/Rover to see if tweaks are necessary
Tactical-1	10:00	Determine if changes need to be made to the plan, implement if necessary
Long Term Planning Meeting (LTPM)	10:30	Long-Term Planning Meeting to update the LTP based upon previous day's activities
Tactical-2	10:00	Determine if changes need to be made to the plan, implement if necessary
Midpoint+STM	12:30	Revue of Morning + Conference style Presentations, Lunch
Tactical-3	10:00	Determine if changes need to be made to the plan, implement if necessary
Strategic	14:30	Planning Process gets inputs into the next day's plan from science
Tactical-4	10:00	Determine if changes need to be made to the plan, implement if necessary
Debrief	16:30	Revue of day's activities, including DL+SCI acquired, anomalies discussed
Leadership Council-2	17:00	Project Management tags up - High Level Meeting, revues day
APAM	18:00	Activity Plan Approval Meeting, ensure implementability of the plan tp 80%

Fig. 7. Meeting schedule at mission control. From top to bottom, this chart shows the timing of surface operations, when command uplinks (blue triangles) and data downlinks (yellow triangles) take place, when the science processes and planning processes are on-shift, when meetings occur in those processes and finally, when the leadership tags up. Below, a description of each meeting can be found. The downtime meetings (LTPM, Midpoint, STM and Strategic) were eventually allowed to float and were scheduled when needed instead of when marked. Thus on some days one or more of the downtime meetings did not take place or were moved elsewhere in the schedule, as appropriate. With contraction of the field day to shorten command cycle #4 to two hours and to drop the rover exploration command cycle (Fig. 5) DL-5 and UL-5 were eliminated and APAM was cancelled. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

participants had a good understanding of their roles and the team was confident in their abilities.

The Mission Control team consisted of 18 members, many of whom had trained in a single 6-h long Operational Readiness Test (ORT) several weeks prior to the deployment. Most had also attended a training session for the processing software of at least one instrument. As such, it was possible to independently staff most of the roles mentioned in Section 3 over the entirety of the two weeks of the deployment. Notable exceptions to the structure described in Section 3 involve the combining of the INCO, WIKI and planning documentarian functional roles within mission evaluation into one position and the typical combination of the strategic SPI, tactical SPI and Sequencer into two positions within planning. Within science interpretation, the titles of the science themes changed from "Shock", "Geochronology", "Resources" and "Ejecta" to "Geochemistry and Mineralogy", "Physical Properties and Structures" and "Geology, Remote Sensing and GIS" in order to better reflect the work being performed.

The meeting schedule changed considerably. The Kickoff/Briefing at the beginning of the day evolved to include a presentation of the strategic plan by the planning team which reduced the need for a separate review. Similarly, the long term planning meeting was eliminated as the size of the Science Interpretation team and the initial lack of data precluded making plans further out than a single day, in most cases. Where such long term planning was required, it took place within the context of the strategic meeting. Likewise, midpoint meetings were nearly always cancelled given how smoothly each process functioned.

Finally, at the beginning of the second week, in order to reduce the workload on the field team, it was decided to eliminate the command cycle at the start of the day. This meant that there was no longer a need for an 18:30 uplink and the Planning Team was shifted to run entirely concurrently with the Science Team. The final tactical meeting, the Activity Plan Approval Meeting or APAM was deleted from the schedule.

Lessons learned:

(1) When buy-in on a plan is achieved sequentially, liaising roles are required to give context to deliverables moving from one process to the next.

(2) When workloads are light for several roles/responsibilities, they may be combined and fulfilled by a single member on a small team without a great loss of fidelity.
(3) Quick turn-around between 2-h command cycles makes it difficult to think strategically. If a quick turn-around is required, a portion of the team should be physically removed from this tactical process to enable this strategic thinking.
(4) Generalized science themes are more effective than constrained themes for dividing the science team.

4.2. Achievement of goals and notable events

The primary goal of the deployment was to go through the cycle shown in Fig. 3 at least once and to acquire at least one sample. The goal of acquiring a sample was satisfied prior to the end of operations on the first day and the entire sampling cycle was achieved by the end of the second day. A further 16 samples would be collected over the remainder of the deployment. This required a sample triage operation on our cores to decrease their total mass to 1 kg. This corresponded approximately to the mass of 10 core samples (see Fig. 8). While this mass is appropriate to the MoonRise Mission, a caching rover might be more comparable to the proposed MAX-C Caching rover for Mars (Beaty et al., 2010) which is envisioned to be capable of returning 2 kg from Mars (Zacny et al., 2011) and likely more from the Moon.

Over the course of the deployment, no command cycle was lost to weather or to problems in mission control and nearly every command cycle was filled with good quality science data. Over the first week of operations, a total of 8.58 Gb of data was returned out of a possible return of 11.56 Gb, representing a filling ratio of 74%.

There were also challenges with which Mission Control needed to deal. On several occasions, the rover became stuck in soft sand or otherwise faulted out. Several times, instruments were mispointed or data was of a poor quality and not all waypoints were achieved on the first attempt. These issues required problem solving at Mission Control to, first of all, understand the nature of these challenges and then to devise a procedure for overcoming them. Specific lessons learned for each component will be discussed in Section 5.

For the second week, there were also roving goals. It was desired to, at a minimum, perform a traverse and use the LiDAR on board the rover to expand the roving map and from there incorporate at least two points near outcrops into a roving network beyond what was established during the first week. This was achieved by noon on the first day of the second week. By week's end, we had expanded the initial landing site to include four other sites with our exploration stopping only because we could find no new easily accessible areas. From that point, we began employing our network-point return capability to the full extent and completed a total of 2.22 km of traversing by the end of the week. A LiDAR map of our traverses is shown in Fig. 10.

Notably, a path that Mission Control judged to be safe from GigaPan images turned out to contain a significant "negative terrain feature". The ROC-6's path planner would have permitted the rover to tumble over this cliff edge, ending the mission. However, had the mission been real, it is anticipated that software for a flight vehicle would be able to track such negative topography better than that currently implemented in the experimental obstacle-detection software. Thus the actions of the team in the field to prevent the loss of the rover can simply be considered a green card on this activity.

Lessons learned:

(1) Processing outcrops in parallel is an efficient way to ensure the maximum data return possible and to reduce forward dependencies between command cycles.
(2) The existence of a rover network simplifies interrogation of past targets and enables parallel investigations by the operations team.
(3) The ability to detect negative topography is key to any autonomous roving system as is an understanding of how the equipment will react when confronted with a challenge.

5. Discussion and lessons learned

This section will present a discussion of elements of the test and of mission control. Where appropriate, lessons learned will be highlighted at the end of each subsection. In most cases, the intended audience is both those planning future missions as well as those planning future analogue tests. Sections meant for a subset of these two groups will be labeled as such.

5.1. Enabling tools for mission control

In addition to the proprietary software used for processing the data from each instrument, there were several tools which were used to communicate information between different members of the team. Four were particularly significant and therefore the advantages and disadvantages of each are discussed here. These were the two data and information dissemination systems (Wiki and Directory Structure), the lunar analogue science planning interface (LASPI) and the ASRL rover station.

5.1.1. Data and information dissemination: wiki and directory structure

Two systems were available for the dissemination of information and data. First, a project Wiki was available which was readable by all. In the weeks leading up to the project, the wiki was a primary source for information

Fig. 8. (TOP) nine of the ten samples chosen by the science team to return to earth, shown in powdered form. So many samples were achieved (18 total) that returning them all would not have been realistic, thus a triage was performed on the 9th day of the deployment. (BELOW) A visual inspection of the raw cores reveals a significant variety of sampled materials with colours ranging from black to white with reddish colours also present. Note that the raw cores do not correspond to the powdered cores shown above. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

about the mission and the Mission Control Architecture to be disseminated to the team. It was also hoped that all data products and all documentation during the mission could also be directed through the wiki.

Unfortunately, the server upon which the wiki was mounted operated slowly, especially when large files were employed. This meant that for Science, use of the wiki for common tasks was cumbersome. Almost immediately, on the first day, the Science processes switched to a fall-back position – a directory structure on a separate server. This was extremely practical for operating with the latest data, but put the Science Processes on a separate system from the Planning process. Since information from the Planning process continued to be posted to the wiki, there were many instances where the identity of a particular data product was difficult to determine (see Section 5.2). Additionally, this required the creation of indexing products within the directory structure as the data products were then separate from the indexes automatically generated on the wiki.

Many of the issues encountered between these two systems could be resolved in one of two ways. First, the wiki server could be upgraded such that it becomes an attractive place for the Science Processes to make use of their data. Or, alternatively, a team member could be assigned to formally link the wiki up with the server structure. From the perspective of staffing Mission Control, the first alternative is more attractive.

Lessons learned:

(1) The entire team should have access to the same structure for team information dissemination, reporting and data storage.
(2) Ideally, this will be the same centralized system for all tasks with sufficiently robust hardware to permit simultaneous access by the entire team.
(3) Such a system should be self-indexing and searchable to the maximum extent possible to permit ease of use and ready access to data products and key parameters.

5.1.2. The lunar analogue science planning interface (LASPI)

LASPI was a tool employed by the Planning Process to track the schedule of activities in the field along with their duration and resource requirements. LASPI was developed in-house at the University of Western Ontario's Centre for Planetary Science and Exploration. A LASPI output plan for the fourth day of the deployment is shown in Fig. 9. This tool, similar in concept to the Phoenix Project's Phoenix Science Interface (PSI) (Fox and McCurdy, 2007) proved invaluable for documenting requested activities. Following the uplink of commands at each DDULT, a copy of the LASPI plan would be published on the wiki and sub-pages would automatically be created for each activity requested. Unfortunately, due to the disconnect between Planning and Science on data dissemination, as discussed in Section 5.1.1, these pages were never used. However, the As-Run plans were a great resource for the Evaluation Team to track the progress of the mission. An issue was that the original Science Plan and what Science data was actually returned was not recorded on the WIKI – this information was instead recorded manually on the door in the Science Room and was most valuable to the Science Team.

The analogue deployment proved to be a good test of LASPI itself and several changes are foreseen in advance of future deployments to increase the functionality of this tool. In particular, it may become possible for LASPI to automate the work of the sequencer within the planning process. Since Sequencing was often the bottleneck in getting instructions to the field, this has the potential to increase the speed and fidelity of the Planning Process.

Lessons learned:

(1) A custom graphical interface for tracking the daily plan is necessary for keeping everyone on-task in a complex mission.
(2) Full integration of this graphical interface (i.e. with the information, reporting and data storage system) is desirable in such a way that all uses it.
(3) An inefficient tool will rapidly be replaced by work-arounds that will not necessarily be accessible to or known by all team members.
(4) The ability of this system to generate machine-readable sequences is desirable. However, this capability does not negate the necessity of having an engineer in the loop for validation, verification and testing of sequences so-produced.

5.1.3. ASRL/UTIAS rover station

The rover station in the Planning Process was provided by the Autonomous Space Robotics Lab, part of the University of Toronto Institute for Aerospace Studies. This station was the primary means for plotting rover traverses, determining orientation of the vehicle for pointing instruments, and uplinking data to the field. As such, this station functioned as both the interface between Mission Control and the Field and also between the Science and Engineering Teams. Typically, the operator was a member of the Engineering Team but was embedded in the Planning Process in Mission Control. At one point in the mission it was decided to employ one of the Science Team members to operate this station. From this demonstration it was learned that while on-network driving is a relatively simple task, accurately determining the location and orientation of new traverses requires an extensive knowledge base including the finer points of the rover's physical systems and its autonomous path planner.

Lessons learned:

(1) Embedding an engineer capable of speaking for the abilities of the rover within the planning room is key to the functioning of the planning room.
(2) A graphical interface that can predict both the end location and orientation of the rover is important to enable the work done by the planning process.

5.2. Conventions

There were several different conventions used for keeping track of observations and data. The Field Team and Science team concentrated on Command Cycles (numbered sequentially from the start of the week), whereas planning assigned each activity a unique non-repeating sequence number. This system worked well during the first week. However, at the beginning of the second week it was necessary, for technical reasons related to the change in instrument configurations (see Section 2.2 above), for the field team to renumber command cycles. This resulted in the field, planning and the science processes getting out of sync with one another. Since neither group spoke the language of the other effectively, it became difficult to request data products across processes. This led to some pointing inaccuracies and a necessity for indexing images that added to the workload of individuals at Mission Control.

Lessons learned:

(1) All conventions should be decided ahead of time and agreed to by all test participants.
(2) Specific non-repeated identifiers are required for all data products and all activities performed over the entire duration of the mission.

5.3. Pre-deployment training

Due to the compressed schedule for the deployment, very little training was possible, compared to a typical planetary landed mission. One walk-through was held over one day to introduce the operations concept and later a 6-h ORT was held with the ROC-6 Rover in a controlled

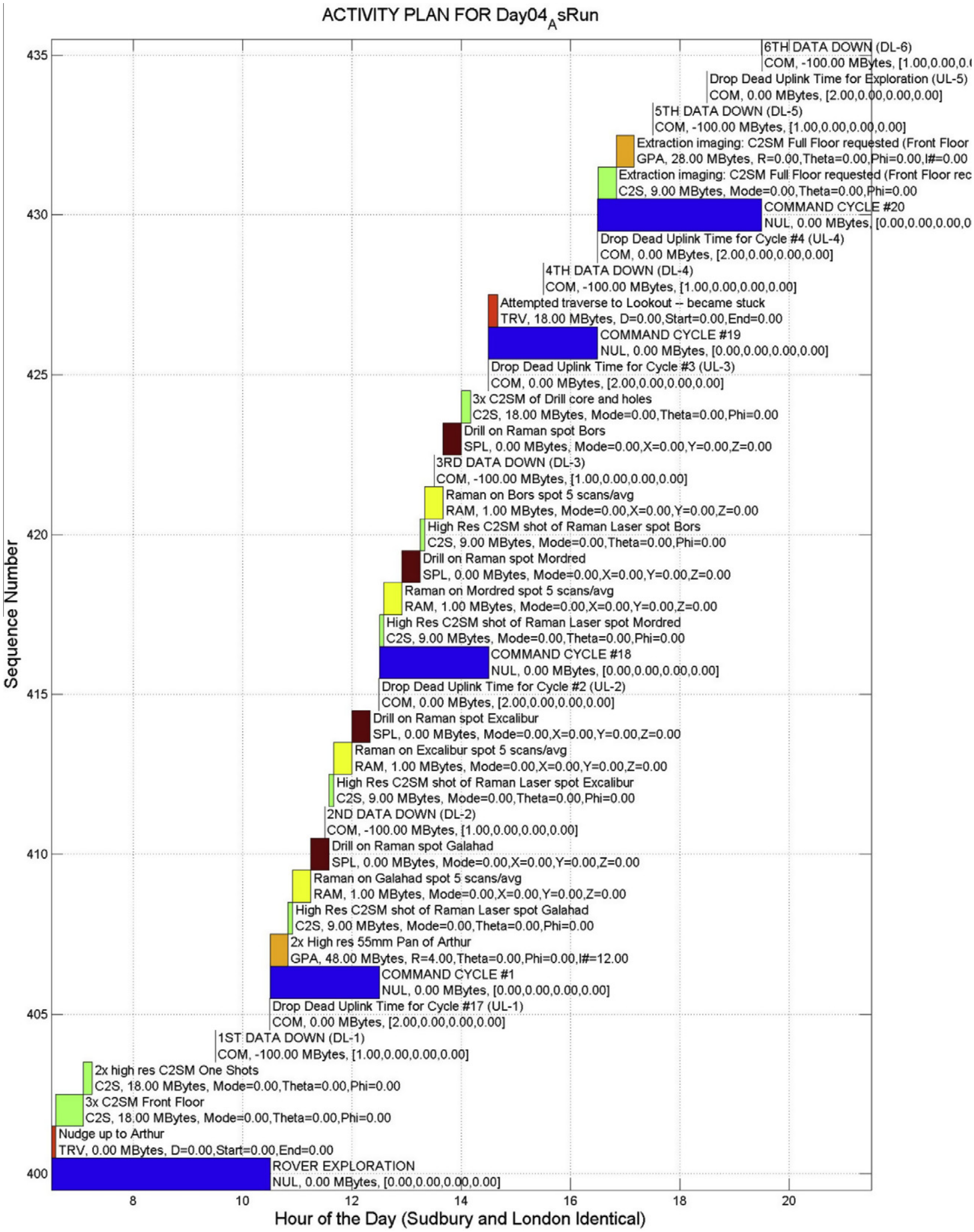


Fig. 9. A typical day's plan as expressed in Lunar Analogue Science Planning Interface (LASPI). LASPI was a scheduling and resources tool employed by the SPIs within the Planning Process and was the chief high-level method of recording what activities were performed. Activities flow from bottom left to the upper right. Day 4 includes a nudge up to the "Arthur" outcrop, Raman analyses of coring sites and sample acquisition. An attempted traverse in Command Cycle 19 to get close to a second outcrop "Guinevere" was unsuccessful. Extraction Imaging in Command Cycle 20 was key to determining the reason for this fault. Note that LASPI expresses data volumes in M Bytes, however, the remainder of this paper uses the spacecraft convention of book keeping data as M bits.

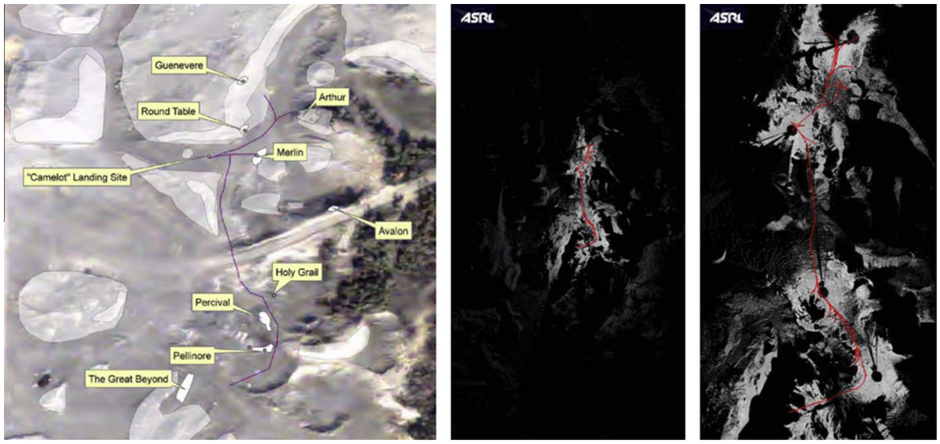


Fig. 10. A map of our traverses in Sudbury. (LEFT) A QuickBird satellite image annotated by the science team to highlight targets of interest. The rover network is highlighted in purple. (CENTRE, RIGHT) Two zoom levels of the LiDAR map acquired. The rover network is highlighted in red with each dark circle representing a new map centre that was stitched onto the whole. The total odometry is 2.20 km and includes one traverse which caused the rover to stop at the edge of a steep drop-off (furthest point towards feature "The Great Beyond" note the dark shadow on the LiDAR map) Another point of interest, shown in the upper right of the rightmost panel was selected due to its high elevation in order to acquire data at long range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environment. While the ORT was successful, there was a lengthy list of issues with the Mission Control Architecture. It is likely that these issues could have been addressed with more extensive training. However, as this was not available, it was decided to modify the Mission Control Architecture to suit the natural inclinations of the group of volunteers who would run the mission rather than attempting to modify those inclinations.

This means that the Architecture that was selected is partially dependant on the specific mix of personalities and expertise present in our Mission Control group. However, as such, the Mission Control Architecture described in this paper was achieved without significant training of the Mission Control Team as compared to typical training efforts. For instance, in preparation for landed Mars missions there may be up to a dozen or more ORTs, each lasting several days. But, since our team was composed primarily of Scientists and most space missions have Mission Control Teams composed mainly of Scientists, our architecture might be broadly applicable, reducing the time requirement for training.

Despite this, it is always preferable to err on the side of more training than less training. ORTs are not only meant to educate the Mission Control Team members, but also to build confidence and, through hard work and shared sacrifice, help the team to come together as a group. By the end of the first week, we had achieved that confidence and camaraderie. However, it would have been preferable to have that in place before the deployment began.

Lessons learned:

(1) Operational Readiness Testing can be used to tailor a mission's operations architecture to a specific group.
(2) As much training as possible is desirable to test out all aspects of the simulation.
(3) ORTs should be as high-fidelity as possible.

5.4. Process flexibility due to small teams

An additional advantage of this architecture is that Mission Control is broken down into more easily manageable teams. The largest team, science processing, requires fewer than 8 people to be effective. In contrast, the Tactical Process for Phoenix required the presence of at least 15 members. While this made some meetings more cumbersome, this representation fulfilled an important purpose. The large number of members was intended to ensure that each instrument, science theme and engineering responsibility had a voice in the main process. Thus, buy-in by all parties on a plan of action could be achieved simultaneously. By contrast, the reduced team size employed within our architecture meant that buy-in on a plan had to be achieved in stages as teams passed off their deliverables to each other (see Fig. 5 for a description of the cycle). Since each added handoff creates the potential for delay and miscommunication, the additional operational flexibility of our scheme comes at a price that may be considered a trade-off.

Lessons learned:

(1) It is possible to achieve buy-in on a plan sequentially rather than simultaneously.
(2) By assigning responsibilities to process leaders and allowing flexibility to alter and define new roles within this responsibility, the team can respond rapidly to changing circumstances and take advantage of opportunities.
(3) Interfaces between processes during operational shifts have the greatest potential for causing miscommunications, misunderstandings and delays.

5.5. 2-H command cycles

The 2-h command cycle was both a negative and a positive for the teams. The quick turn-around lent a frenetic pace to Mission Control and meant that, at times, there was insufficient time available to fully vet a plan of action or to define a traverse or observation. Therefore those activities would often be pushed into the next command cycle, thereby delaying the mission. However, the short turn-around also helped members of Mission Control to remain focused. This, in addition to the volunteer nature of the Mission Control Team, meant that by the end of the second week some members of the team began to feel burnt out. Rolling members of the team on and off the schedule could be a potential countermeasure to this effect. As well, by choosing to use fewer communications opportunities than are available by responding, for instance, once every four hours instead of every two might relax the schedule. A plan to ignore commanding opportunities is common in the Mars Program where there is typically one communications pass per day through which instructions are sent and several passes used only for data and ignored for commanding.

The operations described in the current paper were limited to a small part of the 24-h cycle. However, if the mission were real, it would make sense to support 24-h operations using several shifts. In industrial settings, 24-h operations are typically supported by three 8-h shifts. This would lend itself well to responding to two separate commanding opportunities (for more details on this architecture, consult Bleacher et al., 2010 and Eppler et al., 2011) at 4-h intervals within a single shift for six total commanding opportunities per 24-h period. There are many ways in which phasing of personnel could work and the specific means for extending the operations described herein is beyond the scope of this paper.

By the end of the mission we continued to struggle to determine at what point it was too late to add an activity to a plan. Some observations were simple enough that 15 min before the DDULT was sufficient time to incorporate them. Others were so complex that they needed to be sorted out hours prior to the beginning of a command cycle. In the end, whether or not these activities made it into the plan which was sent to the field was a decision of the Planning Manager on a case by case basis. Ideally, no activity would even be considered by Planning without being fully developed. However, there is a tendency to try and push the envelope of what is possible and as a result, there were several instances where activities that were close to completion needed to be dropped close to the DDULT due to a lack of timing.

Lessons learned:

(1) The size of the team, 18 members, was sufficient for staffing all roles throughout all processes for a single shift.
(2) The pace of operations on a 2-h cycle helps to focus the team.
(3) The pace of operating on a 2-h cycle requires changing out personnel more frequently than once every five days. At a minimum, at least two people should know each role and be capable of swapping in and out after a few days.
(4) Choosing not to command at every opportunity may also help alleviate pressure and fatigue of the team.
(5) Observations should, ideally, be completely fleshed out prior to use. This suggests a validation stage in parallel to the other processes in a fully developed mission architecture.

5.6. Improvements for future analogue deployments

Some improvements are relatively simple, yet can lead to large time savings. First, developing a convention for naming all aspects of the operation beforehand, from downlinked files to uplinked instructions to command cycles can save a great deal of effort and confusion later on. As well, when used correctly, the enabling tools described in Section 5.1 can save a great deal of effort which means that personnel can be redirected to other tasks. The use of LASPI to replace much of the Sequencer's job is one example. Another might be a simple tool to determine the correct pointing for GigaPan segments and C2SM/Lidar one shots rather than performing these calculations by hand. Still another might be to operationally command the rover only once every two orbits. This would mean that command cycles last four hours instead of two. This trades off some flexibility to respond to conditions in the field and allow more forward dependency for more buy-in by Mission Control and longer consideration for measurements at Mission Control. This could ultimately result in higher quality measurements.

Other improvements require additional resources. For instance, a higher-performance wiki/server combination would have helped interfacing between teams. Individual computer stations for all Mission Control personnel would have increased our productivity. More team members would have permitted more work phasing which would have helped to prevent burnout amongst the staff. More training would have helped our confidence and potentially increased our understanding and productivity within the first week.

One lesson which bears repeating is the formation of a leadership council made up of the leaders of each process. With buy-in occurring sequentially instead of simultaneously, it is especially important that the leadership of all processes be on the same page and understand what it is that they are trying to achieve. This was a hedge against the decentralization which could have resulted from breaking up the workload.

Additionally there was added value to having a separate mission evaluation cell, which removed the need for members of the team to think simultaneously at the task, cycle, mission, program, and contract levels, and enabled/improved documentation and process analysis.

5.7. Comment on the division of planning and science

The division between Planning and Science is in some ways a bit unnatural. For a science-driven mission, it makes sense to have Science present at all times to adjudicate the cost to science of various tradeoffs. With Phoenix, each process had science representation to speak to the losses or advantages to deleting or modifying any plan element. In a way, the Science-Planning liaison fulfils this responsibility. However, since planning and science are complementary, it is useful to separate them as has been shown in this Mission Architecture. While each needs the other, the separation creates a friendly tension in both directions that helps to improve the overall plan. Without prioritization of science goals behind observations provided by the science processes, planning does not know how to manage down-selection and tradeoffs motivated by resources. Similarly, without the Planning Process to manage resources and translate desires into low level sequences, Science does not know what can reasonably be requested of the field. Thus, by their very division, Planning puts pressure on Science to communicate their goals as early as possible and in a clear and concise way. Likewise, Science puts pressure on planning to understand ahead of time what the costs and benefits are of performing different operations in the field. This system was found to be awkward at first, but with time, both processes meshed well and became surprisingly effective. At times, this was the result of the leadership of Science being present in the planning room or vice versa. But when this was not possible, the rich and reliable communications provided by a dedicated liaison between the two processes was invaluable.

6. Conclusions

An analogue mission to simulate lunar sample return from the South Pole Aitken Basin was performed at the Sudbury Impact Structure in Ontario, Canada. The simulated scenario consisted of an immobile ascent vehicle and an instrumented exploring/caching rover capable of teach-and-repeat along a network of paths. Both of these simulated ground assets were supported by a single simulated orbiter. In scenario, the orbiter's orbit was similar to that of the LRO Qualification Orbit and was frozen-in such that it did not precess in longitude and had a 2 h period. This 2 h period determined the length of a single command cycle and drove the actions of mission control.

Mission control was modified from that used by the landed Spacecraft of the Mars Exploration Program. However, instead of using large groups to achieve buy-in from all stakeholders simultaneously, a series of small, focused and flexible groups were defined along four processes. Each of these processes gave buy-into a plan consecutively instead of concurrently. These four processes were: science processing, science interpretation, planning and mission evaluation. Science processing was responsible for creating data products from data downlinked from the field and was organized by instrument. Science Interpretation was responsible for determining whether or not science goals are being met and what measurements need to be taken to satisfy these goals. These measurements were then vetted by the instrument-specific expertise within science processing. Next, planning scheduled and sequenced these measurements identified by the first two processes. Meanwhile, the evaluation process monitored and improved inter-process communications and documented the actions undertaken at Mission Control. Uniting these processes was a leadership council made up of process leaders. This council kept all processes on the same page at all times. Between council meetings, inter-process liaisons assisted in the flow of information and products from one process to the next.

This division of activities created constructive tension between planning and science processing and allowed the necessary elements of mission control to be staffed with a small number of people. This architecture would therefore permit operations to be carried out by small teams and would permit more members of Mission Control to participate in the Science Interpretation process.

Site characterization was conducted by Mission Control from large-scale to small scale. Initially, the posture adopted was to perform this characterization in a serial mode, proceeding from large to small scale on a single target. However, with the acquisition and successful caching of the first sample inside the ascent vehicle, a posture was adopted in which many sites were investigated in parallel. This allowed more efficient use of each command cycle by removing forward dependencies between adjacent command cycles. Furthermore, a rover with a teach and repeat architecture is the ideal platform to conduct this kind of parallel investigation since points on the rover network can be returned to at very little cost once visited initially. Thus, the robotic network employed is similar to that used for the Phoenix Robotic Arm. Over the course of 10 days, 18 rock samples were collected from 5 outcrops, 182 field activities were completed within 43 command cycles, and the rover travelled over 2200 m. The limited data budget was filled at a rate of 74%. Finally, sample triage was simulated to allow down-selection to 1 kg of material for return to Earth. Thus this division of responsibilities helped the Mission Control team to achieve the goals of the analogue mission within its constraints.

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