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Lunar polar rover science operations: Lessons learned and mission architecture implications derived from the Mojave Volatiles Prospector (MVP) terrestrial field campaign

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Abstract

The Mojave Volatiles Prospector (MVP) project is a science-driven field program with the goal of producing critical knowledge for conducting robotic exploration of the Moon. Specifically, MVP focuses on studying a lunar mission analog to characterize the form and distribution of lunar volatiles. Although lunar volatiles are known to be present near the poles of the Moon, the three dimensional distribution and physical characteristics of lunar polar volatiles are largely unknown. A landed mission with the ability to traverse the lunar surface is thus required to characterize the spatial distribution of lunar polar volatiles. NASA's Resource Prospector (RP) mission is a lunar polar rover mission that will operate primarily in sunlit regions near a lunar pole with near-real time operations to characterize the vertical and horizontal distribution of volatiles. The MVP project was conducted as a field campaign relevant to the RP lunar mission to provide science, payload, and operational lessons learned to the development of a real-time, short-duration lunar polar volatiles prospecting mission. To achieve these goals, the MVP project conducted a simulated lunar rover mission to investigate the composition and distribution of surface and subsurface volatiles in a natural environment with an unknown volatile distribution within the Mojave Desert, improving our understanding of how to find, characterize, and access volatiles on the Moon.

Keywords: Moon; Volatiles; Rover; Missions

1. Introduction

The study of lunar volatiles has garnered significant interest in both the science and exploration communities because of the importance of understanding the scientific basis for such deposits and the potential use of volatiles to enable future lunar exploration. Scientifically, the presence of volatile deposits on the Moon is of importance to in order to understanding the inventory, emplacement mechanisms, and evolution of volatile deposits on airless bodies in the solar system. Lunar volatiles are also of importance for exploration as a potential in situ resource

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to support future robotic and/or human missions to the Moon.

Volatile deposits have long been considered to exist near the lunar poles, particularly in permanently shadowed regions that are difficult to access with surface assets (Watson et al., 1961; Arnold, 1979). NASA's LCROSS (Lunar Crater Observation and Sensing Satellite) mission confirmed the presence of volatile compounds within the permanently shadowed Cabeus crater near the lunar south pole (Colaprete et al., 2010). However, a subsequent intriguing finding from the Lunar Reconnaissance Orbiter (LRO) mission is the possibility of polar volatile deposits located just centimeters below the lunar surface in areas that receive only a few days of sunlight each month (Paige et al., 2010; Mitrofanov et al., 2010; Beyer et al., 2011; Heldmann et al., 2012). These deposits would be much more accessible than volatiles found in permanent shadow and thus could be explored in situ by a solar powered rover on the Moon.

Conducting such a lunar rover mission requires a novel concept of operations since this mission would be of limited duration (e.g., the few days of the month when the region is in sunlight) and would necessitate near real-time operations by a dedicated Science Team to rapidly synthesize the rover science data and make operations decisions. This rapid pace of operations is necessary to maximize the mission productivity for the limited duration window of surface operations.

Spaceflight experience with short-lived planetary rover missions is limited, and thus the Mojave Volatiles Prospector (MVP) project was developed to improve our understanding of how to find, characterize, and access lunar volatiles with a short duration solar powered rover mission. In particular, the MVP field campaign was specifically designed to investigate various modes of robotic navigation and Science Team participation to assess the feasibility of conducting this new class of robotic planetary mission and report on lessons learned to maximize the efficiency and productivity of such a mission.

Since a lunar rover mission to investigate polar volatiles is significantly different from human spaceflight or robotic surface missions, this mission design requires a new concept of operations. The lunar rover must navigate 3–5 km of terrain and examine multiple sites in a very short time, e.g., days, to adequately characterize the lunar volatiles (Heldmann et al., 2012). Operational decisions must be made in near real time throughout the mission and commanded remotely, requiring immediate situational awareness, data analysis and decision support tools. This operations scenario is different from our previous experience with different types of space missions such as the long delay and intermittent communications with Mars rovers (daily command cycles), or human-in-the-loop, rehearsed procedure execution of human spaceflight.

To inform the mission architecture of MVP, we use NASA's Resource Prospector (RP) mission as a case study. RP is a mission currently in formulation (Phase A) by NASA's Human Exploration and Operations Mission Directorate (HEOMD) to both prospect for water resources and conduct in situ resource utilization (ISRU) on the Moon (Andrews et al., 2014; Colaprete, 2014). For prospecting, RP is designed to characterize the distribution of water and other volatiles at the lunar poles. RP aims to map the surface and subsurface distribution of hydrogen-rich materials within the upper ~1 m of the Moon, determine the constituents and quantities of volatiles, and provide limits on key isotope ratios (e.g., D/H, O^{18}/O^{16}, S^{36}/S^{34}, C^{13}/C^{12}). RP is also an ISRU processing demonstration mission to demonstrate the hydrogen reduction process to extract oxygen from lunar regolith. RP will both demonstrate ISRU hardware in the lunar setting and also capture, quantify, and display the water generated from the ISRU processing (Andrews et al., 2014; Colaprete, 2014).

1.1. Lunar polar volatiles

Scientists have long considered the possibility that water ice deposits may exist in permanently shaded craters near both lunar poles (Watson et al., 1961; Arnold, 1979). The floors of permanently shadowed craters should be extremely cold (<100 K) (Vasavada et al., 1999) and indeed LRO Diviner has measured some permanently shadowed regions as colder than 40 K. There are several pathways by which volatiles can become trapped in a permanently shadowed region. For example, a significant number of water molecules delivered by meteoric infall can survive loss processes, find their way to these craters and be cold-trapped for billions of years (Butler, 1997). Implanted solar wind hydrogen could yield impact-liberated water molecules, leading to enhanced hydrogen in polar shadow (Crider and Vondrak, 2003). Indeed, NASA's LCROSS (Lunar Crater Observation and Sensing Satellite) mission measured ~5 wt% water in Cabeus crater (Colaprete et al., 2010). In addition, recent subsurface temperature modeling based on LRO Diviner data suggests that ice can be stably trapped for long periods of time (billions of years) even in polar locations that receive small amounts of oblique sunlight at solstice (Paige et al., 2010).

However, the distribution of cold-trapped water ice (and other volatiles) near the lunar poles is unknown at scales less than a few tens of km. Neutron data from Lunar Prospector and LRO have indicated the presence of polar hydrogen enhancements (Fig. 1; Feldman et al., 1998, 2000, 2001; Lawrence et al., 2006; Elphic et al., 2007a; Mitrofanov et al., 2010, 2012), and anomalous bistatic radar returns from the Clementine lunar orbital mission have been interpreted in terms of icy materials (Nozette et al., 1996, 2001). However, Earth-based radar imaging of the Moon has not revealed large, bright, depolarized features like those seen at Mercury (Stacy et al., 1997; Campbell et al., 2003, 2006). If cold-trapped volatiles are truly only concentrated in limited areas, then orbital techniques are not sufficient to localize these deposits. Only by

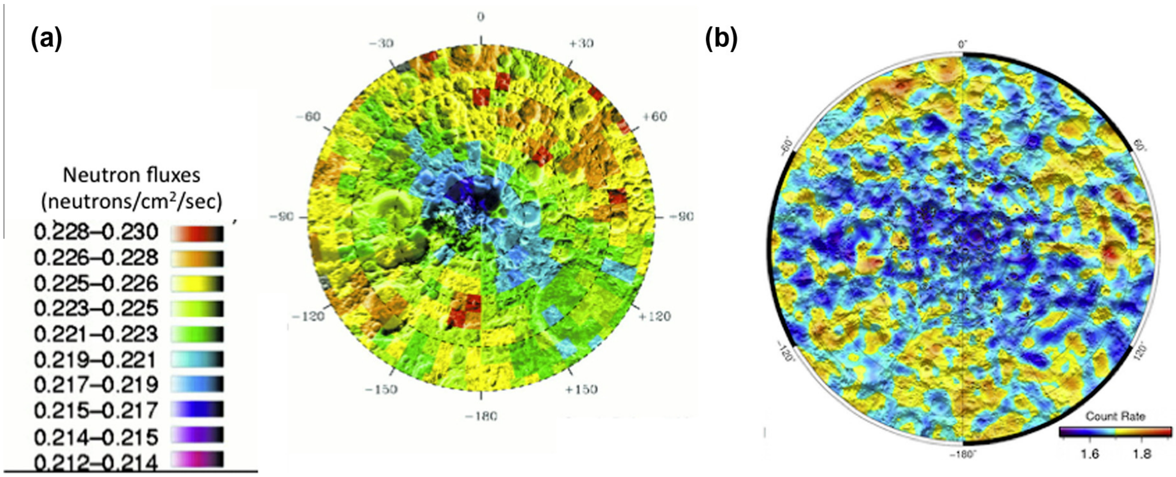

Fig. 1. Neutron spectrometer data from Lunar Prospector ((a) adapted from Feldman et al. (1998)) and Lunar Reconnaissance Orbiter ((b) adapted from Mitrofanov et al. (2012)) indicative of enhanced hydrogen near the lunar south pole. Note lower neutron counts (blue-purple locations on the map) indicate higher hydrogen abundance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

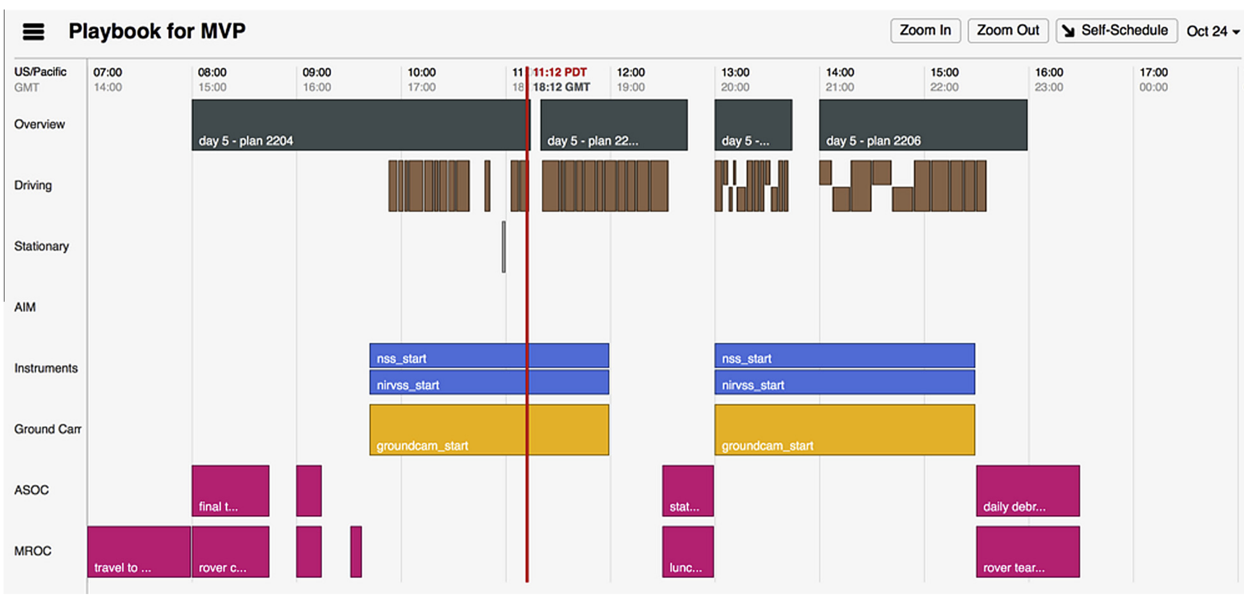

Fig. 2. Playbook timelining software used during MVP operations. Playbook visually represents the times and durations of key mission activities. Time is shown across the top of the Playbook screen. Color coded blocks indicate various activities and their durations during the operational timeline. Black indicates periods of rover operations, brown indicates times when the rover is driving, blue indicates the times when the science instruments (NIRVSS and NSS) are operating, yellow indicates when the GroundCam is active, and pink indicates SOC and ROC activities such as debriefs or lunch. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

exploring the lunar surface at smaller than km scales can we determine unambiguously the presence, abundance, composition and spatial distribution of cold-trapped volatiles.

Since the LCROSS mission impacted into an area of permanent shadow within Cabeus crater near the lunar south pole and detected on the order of 5 wt% water ice (along with multiple other volatile species), we have evidence that at this one location near the lunar south pole, volatiles do indeed exist in significant quantities (Colaprete et al., 2010). However, because of its localized nature, LCROSS did not tell us about the spatial distribution of volatiles in other areas within Cabeus or elsewhere near the poles of the Moon. Additional finer scale data is required in additional regions on the Moon to further characterize the spatial distribution of lunar polar volatiles.

We also note that surface-bound volatiles have also been detected on the Moon. Remote sensing data from the Moon Mineralogy Mapper (M3), Deep Impact (EPOXI), and Cassini missions indicated the presence of surface-bound volatiles (adsorbed OH/H_2O) on the lunar surface in areas of sunlight (Pieters et al., 2009; Sunshine et al., 2009; Clark, 2009). Since these volatiles are observed in areas of sunlight, they may be easily exploitable since they do not necessarily require cold temperatures and/or permanent shadow. The OH and H_2O desorbed from regolith grains at lower-latitudes could also be a source for cold traps at high latitudes. These surface-bound volatiles are expected in very thin layers on the lunar surface and are thus not as volumetrically abundant as the expected subsurface ice and volatiles near the lunar poles. For this reason, both RP and MVP are focused on studying the higher concentration volatile deposits near the poles of the Moon.

1.2. Case study: Resource Prospector mission

For this work we consider NASA's Resource Prospector (RP) mission as a notional case study to inform the development of MVP. RP has the main goals of (1) confirming the presence of lunar volatiles and measuring their distribution and (2) determining if these volatiles are exploitable to enable future lunar exploration. RP will investigate a sunlit region near a lunar pole where volatiles are expected in the near subsurface (Andrews et al., 2014; Colaprete, 2014). Subsurface and surface-bound volatiles are expected in regions of short duration daylight whereas only surface-bound volatiles are expected in more persistently lit sites (Beyer et al., 2011; Heldmann et al., 2012).

The RP rover mission is unique compared with previous missions that have been proposed to land near the Moon's poles. Several previous mission concepts have focused on a static lander in a region of persistent light (such as the rim of Shackleton Crater) to enable long-duration operations (Fristad et al., 2004; Kring and Rademacher, 2007; Plescia et al., 2008). The lunar polar volatile rover mission, however, has a scientific and exploration focus of locating and characterizing volatiles. This mission goal has two important implications for mission architecture: (1) mobility is required to determine the spatial distribution of volatiles and (2) the landing site must be in an area expected to harbor polar volatiles. For #1 (mobility), the mission requires the use of a rover capable of traversing the lunar terrain and acquiring the needed measurements to locate and characterize the volatiles. For #2 (landing site), the need to land where volatiles are expected drives the landing site to a region where volatiles are stable in the near-subsurface. Surface-bound volatiles (OH and H_2O) may be stable in areas of persistent sunlight, although subsurface volatiles require cold temperatures for retention, which is incompatible with a persistently sunlit site. However, recent LRO data and modeling suggests that temperatures are cold enough just below the surface (cms to 10 s of cm depth) to retain volatiles in regions that are sunlit for just several days each month (Paige et al., 2010). Recent LEND data also suggests that hydrogen, possibly in the form of volatiles, is present in the near-subsurface in these same sunlit regions (Mitrofanov et al., 2010, 2012). Therefore the mission to study both surface and subsurface volatiles can be achieved in sunlight (permanent shadow is not required), which greatly simplifies mission operations and rover design. The mission therefore is optimized as a solar-powered rover operating at a polar site that experiences direct sunlight for several days per month (Beyer et al., 2011; Heldmann et al., 2012; Andrews et al., 2014; Colaprete, 2014).

The notional measurements for studying both surficial and subsurface volatiles have been identified for this mission concept (Beyer et al., 2011; Heldmann et al., 2012; Andrews et al., 2014; Colaprete, 2014). To study the subsurface volatiles, the rover aims to (1) confirm the presence (or absence) of volatiles in locations identified via remote sensing data, (2) quantify the spatial distribution (lateral and vertical) of volatiles, (3) quantify the form, amount and accessibility of volatiles, and (4) characterize the influence of topography, surface mineralogy, grain sizes, etc. on volatile retention. To study the surface-bound OH–H_2O, this rover aims to (1) confirm the presence (or absence) of adsorbed OH and H_2O in sun-lit regions, (2) quantify the daily cycle of OH/H_2O production, (3) determine if OH/H_2O is a volumetrically important resource, (4) characterize the influence of topography, surface mineralogies, grain sizes, etc. on volatile retention.

The unique nature of RP with limited duration operations primarily in sunlight has required the development of a specific concept of operations (conops). The nominal mission profile includes the rover landing in an area illuminated by the sun and then traversing across the lunar surface to characterize the surface and subsurface volatiles. To achieve the mission objectives and operate within the given mission constraints, RP is constrained to only 4–6 days of operations (Andrews et al., 2014; Colaprete, 2014). The mission duration is a balance between targeting the most scientifically compelling region(s) that have high hydrogen abundances (and hence inferred high volatile content) and are located in proximity to shadowed areas for targeted shadow investigations. These areas are by default relatively cold (e.g., high polar latitude) and only experience a few (∼4–6) days of sunlight each month.

In addition, the RP Science Team will be monitoring the prospecting data from the prospecting payload in real-time and making real-time operational decisions based on the data return. The RP surface conops has multiple modes of operation critical to mission success including (1) prospecting, (2) Excavation, (3) mapping, and (4) demonstration. In prospecting mode, the RP rover is traversing across the lunar surface as the prospecting instruments search for enhanced H_2O/OH, other volatiles, and/or volumetric hydrogen. When enhancements of volatiles are detected, a decision is made by the mission team in real-time whether or not to auger or core into the subsurface (e.g., collect subsurface samples). Once a decision has been made in the affirmative to collect samples, the rover enters Excavation mode where samples are acquired from the subsurface, processed by the onboard payload, and evolved gases are measured to characterize volatile content. Prospecting mode can continue throughout the primary mission as the rover maps volatiles and samples across a variety of environments, testing theories of emplacement and retention, and constraining the economics of extraction. Demonstration mode occurs at the end of the RP primary mission when oxygen extraction from the regolith is demonstrated using hydrogen reduction, thus testing two possible ISRU pathways: (1) ISRU from local volatiles and (2) water production from "dry" regolith (Sanders and Larson, 2015). At the crux of the RP operations is the real-time nature of the mission operations. The mission architecture and conops is intimately dependent upon an effective and efficient mode of decision-making and communication within the science and mission operations teams to enhance and enable the scientific return from such a real-time operations planetary rover mission.

2. MVP overview

To test concepts of science operations and provide feedback to inform future robotic exploration of the Moon, the MVP project conducted a terrestrial field campaign to integrate a lunar polar volatile prospecting payload to a terrestrial rover and operations software system. The MVP mission was specifically designed as an analog mission with respect to RP. Specifically, MVP utilizes the same payload elements (Near InfraRed Volatiles Spectrometer System (NIRVSS) and Neutron Spectrometer System (NSS)) as RP (Section 2.1), operated at a lunar-relevant analog field site (Section 2.2), designed an operations setup with analogous operational architecture and decision-making protocols as RP (Section 2.3), operated with the same rover modes of investigation as planned for RP (Section 2.4), and used similar software packages and capabilities as planned for RP (Section 2.5).

2.1. MVP payload and rover

The MVP rover mission was predicated on the RP lunar mission and thus used similar payload elements, concepts of operations, and ground data systems. Similar to RP, MVP used two main prospecting instruments to map out the distribution of water, a neutron spectrometer and a near-infrared spectrometer system. For MVP we used the NSS (Neutron Spectrometer System) and NIRVSS (Near InfraRed Volatile Spectrometer System). NIRVSS is used for assessing surficial hydration and mineral mixtures sensitive to hundreds of micron depths as well as subsurface volatiles when samples are brought to the surface. The NSS is used to gauge volumetric hydration and elemental composition variations non-invasively within the top decimeters (Elphic et al., 2007a, 2007b, 2008a, 2008b, 2015a; Roush et al., 2015). NSS and NIRVSS are being matured for flight on the RP mission, both in terms of technology readiness level as well as the novel concept of operations proposed here (Colaprete, 2014). MVP also used a downward facing GroundCam camera on the KRex-2 rover (Fig. 3) to investigate the relationship between the distribution of volatiles and soil crust variation in the Mojave Desert.

MVP used the KRex-2 rover, designed and operated by the Intelligent Robotics Group at NASA Ames Research Center (Fig. 3). KRex-2 is a four wheel drive, four wheel steer vehicle with a wheelbase of ~1.8 m and ATV wheels 26 inches in diameter. The overall size of KRex-2 is approximately 2.0 m × 1.6 m and the rover weighs about 300 kg. For MVP, the NSS, NIRVSS, and GroundCam payload elements were mounted onto the rover, and the rover was integrated with the xGDS software to execute pre-planned traverse paths and relay data to the Science Team for real-time monitoring and decision making. KRex-2 is not a lunar analog rover in terms of rover engineering aspects such as power, thermal or communications systems, but instead provides the capability of traversing lunar-like terrain while carrying scientific instrumentation for field testing. The rover operated at a nominal speed of 10 cm/s which is the optimal speed for acquiring data with the NSS.

2.2. MVP Field Site

The MVP rover operations were conducted in the Mojave Desert, selected for its low, naturally occurring water abundance similar to the expected water abundances near the poles of the Moon. The Mojave typically has on the order of 2–6% water (Webb, 2002), making it a suitable lunar analog for this field test.

The field site was located in the Mojave Desert, California (Fig. 4a). The test site was an alluvial fan just east of the Soda Mountains and southwest of Baker, California. This site contains desert pavements ranging from the late Pleistocene to early-Holocene in age, is located at an elevation of ~450 m, and is within an arid environment which receives an average of 12–25 cm mean annual precipitation each year. The present-day Mojave Desert climate is primarily the result of the rain-shadow effect of the high-altitude Transverse Ranges and the Sierra Nevada, located 100–200 km to the west/southwest and northwest (McFadden et al., 1986). Much of the precipitation falls during relatively cool winters. Vegetation in the study area is spotty in location and classified as the Mojave Desert scrub community (Brown et al., 1980). Fig. 4b shows the immediate field test locale on the fan; the magenta outline defines the boundary of the exploration area. Based on orbital imagery, hyperspectral data and topography, the fan was divided into three Objective Areas (OAs), shown by purple outlines. OA-A is in the mid-southern half of the fan, and contains a variety of terrain types within a limited area – dark, heavily desert-varnished pavement stretching from the upper fan down to a wash-cut terminus, lighter-toned pavements, active washes (gullies and channels) formed by flash floods, and areas of bar and swale. OA-B contains much of the northern half of the fan, and includes several different desert pavement types for contrast with the southern portions of the fan. OA-C contains

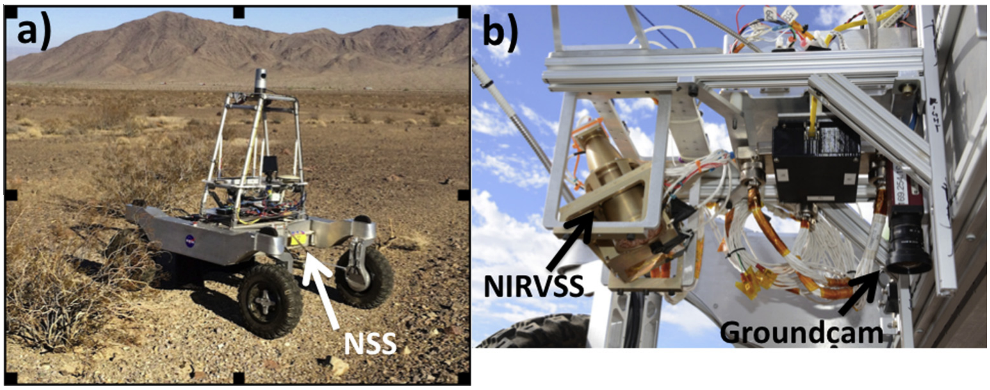

Fig. 3. KRex-2 rover traversing desert pavements and nearby features during the MVP test. (a) The NSS (Neutron Spectrometer System) instrument is labeled and mounted on the rear of the rover. (b) The NIRVSS (Near InfraRed Volatiles Spectrometer System) and GroundCams are labeled and mounted on the front of the rover.

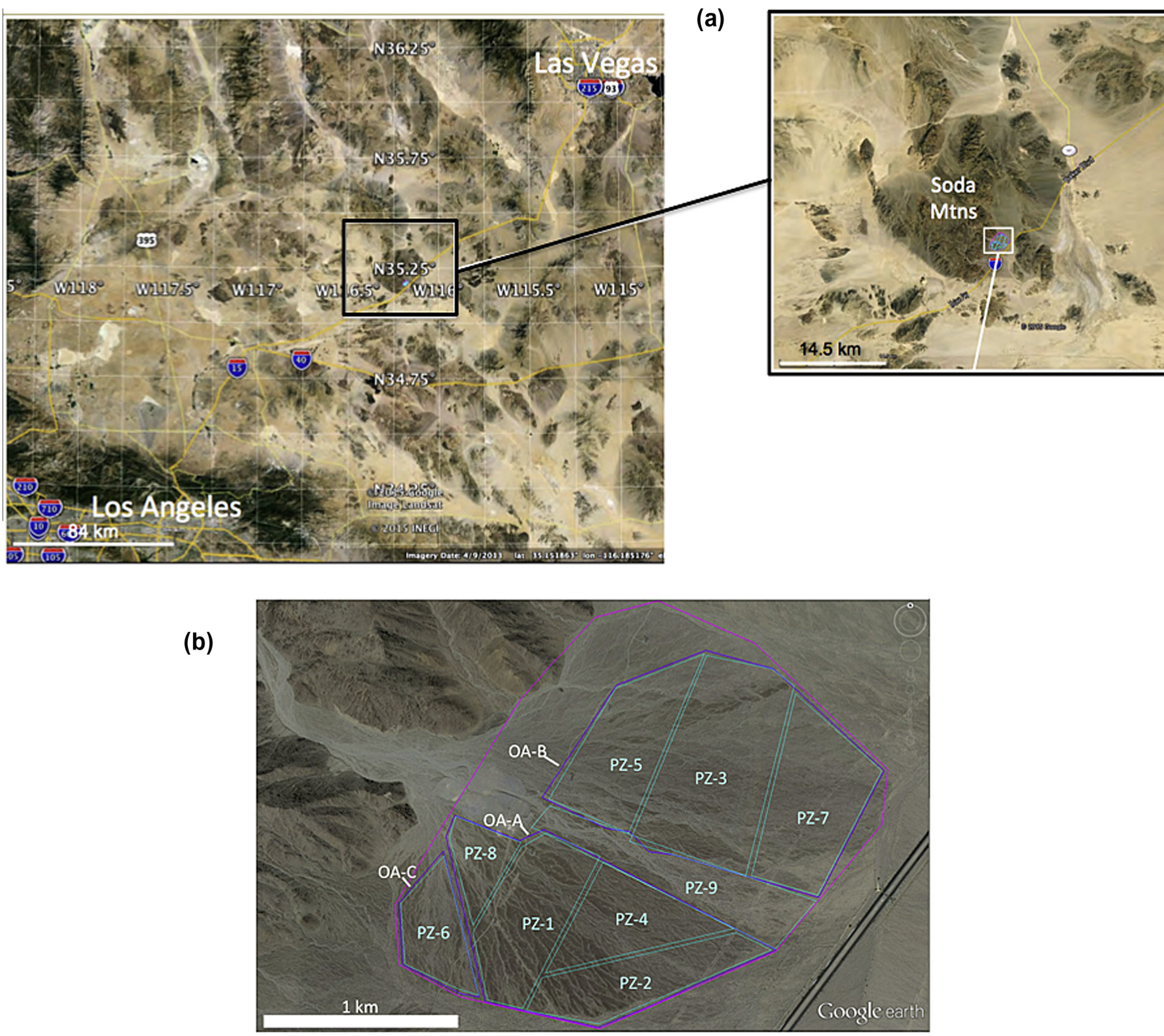

Fig. 4. (a) Location of the MVP field site in the Mojave Desert (adapted from Elphic et al. (2015b)). (b) MVP field site strategic planning units. Large Objective Areas (OAs) and smaller Prospecting Zones (PZs) are shown numbered by priority rank.

the western-most portion of the fan and exhibits further pavement variety. Also shown are Prospecting Zones (PZs), which define areas that can be explored within roughly one day of rover operations. The PZs were also prioritized based on the variety of pavements and other features within them, and thus the anticipated range of possible hydration across those features. Traverse plans were generated a priori for each PZ.

We chose to conduct MVP in this region of the Mojave Desert since this area is a suitable lunar analog for this work based on the properties of low, naturally occurring water abundance in an arid environment. The spatial distribution of the soil water content is unknown in both the Mojave and on the Moon, however both locations have low water abundance. LCROSS measured ~5% water in Cabeus Crater on the Moon (Colaprete et al., 2010). Compared with deserts on Earth, the Sahara has only 2–3% water while the Mojave typically has on the order of 2–6% water (Webb, 2002), making the Mojave Desert an ideal lunar analog for this field test.

2.3. MVP operations team

The architectural design of the MVP science and rover teams was based on previous field testing and coordination with NASA's RP mission team. Prior field testing in 2012 in Hawaii used a lunar rover analog equipped with similar instrumentation as MVP (NSS and NIRVSS) which resulted in the identification of key science operations personnel for a real-time operations rover mission (Heldmann et al., 2015b). The MVP team also coordinated with NASA's Resource Prospector (RP) mission team regarding RP needs and best practices to optimize the MVP architecture (Andrews et al., 2014).

MVP conducted a simulated lunar polar rover mission using a concept of operations based on the conops for the RP mission. Voice loops (discussed in detail in Section 3) were used to enable communications among the various operations personnel during MVP. The NASA KRex-2 rover was operated in the Mojave Desert by a remote Science Operations Center (SOC) located at NASA Ames Research Center and a Rover Operations Center (ROC) located in the Mojave, with each location staffed with specific console positions (Fig. 5). A Science Backroom was also located at NASA Ames where scientists typically conducted more in-depth data analysis during the mission. We note that both MVP and RP contain elements of the SOC, ROC, and Science Backroom in the conops. Console positions are common to both the terrestrial MVP mission and the notional concept of operations for the lunar RP mission, except where noted below in terms of added positions required to support the field-based component of MVP. MVP team members in the ROC stayed on the same console positions for the duration of the field test since each console position had one dedicated and trained team member. Team members on the SOC tended to rotate to different positions when more than one person was qualified and trained on a console position in order to provide more personnel with the console experiences.

2.3.1. Science Operations Center

The Science Team generates traverse plans for the rover, monitors real time telemetry coming from the rover, and analyzes instrument data, plots, and maps in real time to determine when spatial heterogeneity is encountered and how to most effectively explore and document the variability and its relationship to surface geomorphology. The Science Team also evaluates the efficacy of the science operations tools in assisting with this work. The Science Operations Center (SOC) has strong situational awareness as science data and rover imagery are projected on screens in the SOC and available for viewing at each console position.

In order to complete these myriad Science tasks, the MVP Science Team consisted of several dedicated console positions specifically designed to enable the real-time operations component of this mission scenario. These console positions are described below and shown in Fig. 5.

2.3.1.1. Test Director. The Test Director position is unique to the MVP field campaign and is not a console position for a lunar mission since the Test Director's main responsibilities focused on coordination with the rover field team, and there would be no field team onsite with the rover for a lunar mission. However, for MVP, the Test Director provided direction of activities in the field, informed the team of any factors influencing field test goals and objectives, directed real-time field activities ensuring safe operation of the rover and payloads, prioritized field activities to maintain progress versus the field test timeline, ensured field operations team maintained situational awareness of rover and payload operations, and ensured adherence to flight rules and procedures while operating in the field.

2.3.1.2. Science Operations Manager (SOM). The SOM is responsible for the overall science management for the mission and ensures that the strategic mission goals are being accomplished to the best of the mission's capability.

2.3.1.3. Science Lead (Sci Lead). The Sci Lead has primary responsibility for the tactical science plans to be executed by the rover. Sci Lead provides science-based rover operations recommendations to the rover team, interfacing with the SOC, and informing the SOM and Rover Lead of relevant activities.

2.3.1.4. Science Communicator (Sci Comm). Sci Comm aggregates and synthesizes the input from the collective Science Team, and provides this information in a timely, accurate manner to the Real Time Science position.

2.3.1.5. NIRVSS Science (NIRVSS Sci), NS science (NS Sci), camera science (Camera Sci). The NIRVSS Sci, NS

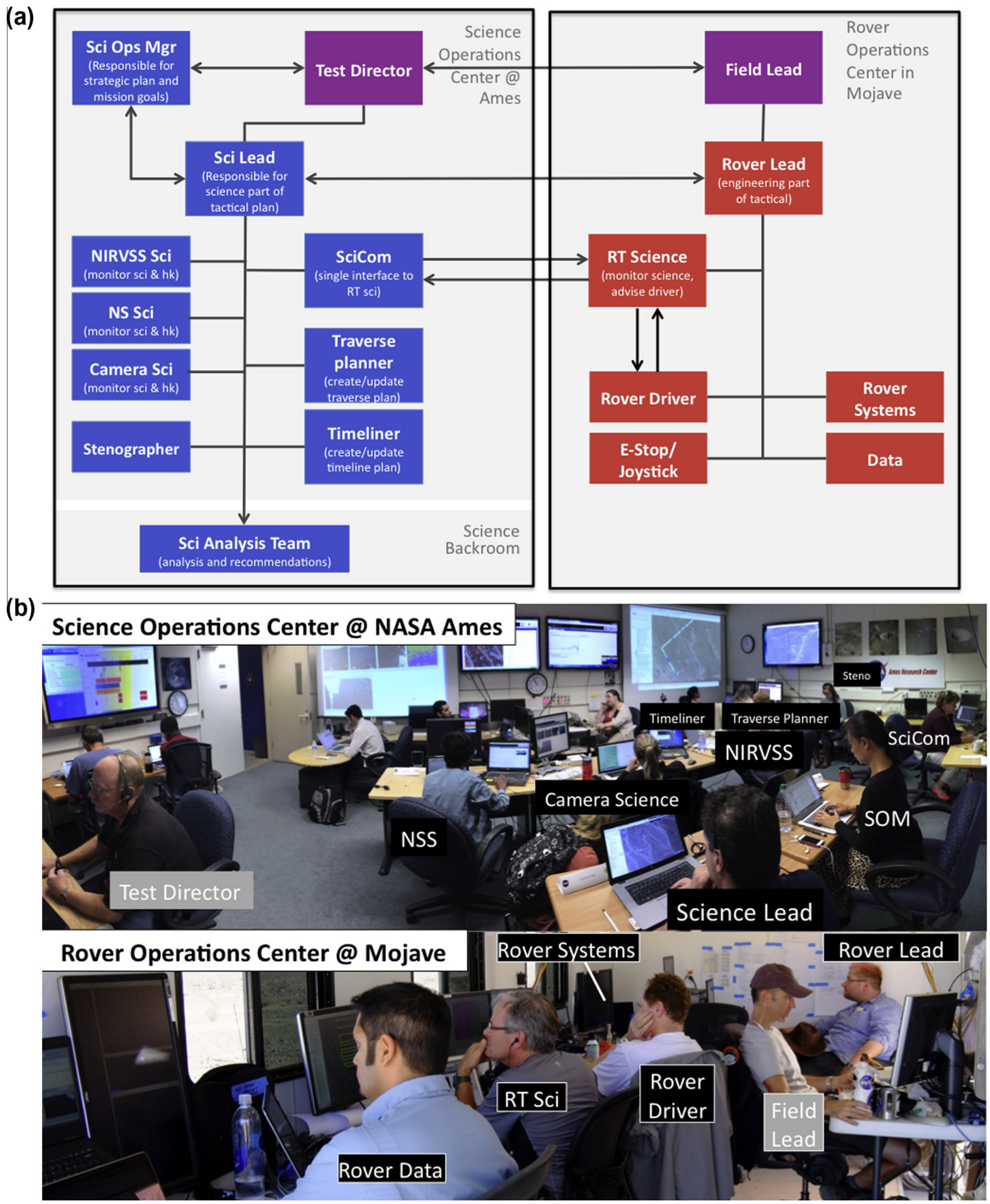

Fig. 5. (a) Schematic diagram of MVP console positions within the Science Operations Center (SOC) at NASA Ames Research Center and Rover Operations Center (ROC) in the Mojave Desert. (b) Staffed MVP Science Operations Center (SOC) and Rover Operations Center (ROC) during the MVP field deployment. Console positions unique to the MVP field test and not anticipated for the RP mission are indicated by gray boxes (Test Director and Field Lead).

Sci, and Camera Sci console positions are tasked with monitoring the real-time NIRVSS, NS, and camera data, respectively, to provide integrated, event-level information and operations recommendations based on the real-time telemetry stream. These instrument analysis positions are responsible for providing updated operations recommendations based on the tactical and strategic aspects of the data analysis.

2.3.1.6. Traverse Planner. The Traverse Planner must coordinate with the Science Team to generate updated traverse plans and rover activities based on the incoming science data. The Traverse Planner must coordinate with the Sci Lead and mission management to ensure the updated rover plans are provided to the rover team for timely execution and are compliant with mission rules and constraints.

2.3.1.7. Timeliner. The Timeliner maintains an updated mission timeline based on the real-time updates to the rover activities and traverse plans. The Timeliner must also work with the Traverse Planner to ensure that any updated plans are consistent with the available mission time.

2.3.1.8. Stenographer. The Stenographer records mission activities and events within the xGDS platform. These notes provide an easily accessible format for further science analysis and can be cross-correlated with the science instrument datasets through timestamp matching.

2.3.1.9. Science Analysis Team. A Science Analysis Team is located in the Science Backroom and primarily conducts more in-depth science analysis of the data than can be accomplished by the scientists serving on console positions in the Science Operations Center. Additional important information can be gleaned from a more detailed analysis of the payload instrument data, and such information may be important for both improving our scientific understanding of the research site and thus may also impact the strategic planning for the rover operations during the mission. Since the scientists in the Backroom are busy conducting detailed analyses of the instrument data, they do not have as much situational awareness compared with the SOC. The Backroom is not as intimately connected to real-time operations, and instead of monitoring the rover progress in detail, the Backroom team is focused on understanding details of the data itself. During MVP, the Science Backroom analysis tended to provide supporting evidence and confirmation of preliminary interpretations of the data inferred by the SOC. Approximately 5–6 people served in the Science Backroom at a given time. However, this staffing profile was a result of MVP personnel availability and budget constraints. The optimal size of the Science Backroom warrants further investigation.

2.3.2. Rover Operations Center

The rover team has responsibility for safe operation of the rover, uploading and initiating execution of plans, monitoring systems, manually controlling tasks that are not in the plans, and providing input to the Science Team during planning, and feedback during execution when problems are encountered.

These console positions are described below and shown in Fig. 5.

2.3.2.1. Field Lead. The Field Lead position is unique to the MVP field campaign and is not a console position for a lunar mission. However, for MVP, the Field Lead provided overall leadership for the field activities and coordinated all rover work in the Mojave Desert. The Field Lead coordinated with the Test Lead in the SOC to relay any field-specific information that would affect mission operations, ensured safe and proper execution of field activities, and provided guidance and planning support to enable the science-based field investigation.

2.3.2.2. Rover Lead. The Rover Lead is responsible for safe operation of the rover and payload, for the execution of the engineering aspects of the current tactical plan (including considerations of technical limitations such as power and communications availability), and coordinates with the SOM regarding the status of the execution of the tactical plan, power and other resources, and approves the upload of new traverse plans to the rover.

2.3.2.3. Real Time Science (RT Sci). RT Sci is the primary interface between the science operations team and the rover operations team. The RT Science operator is a scientist on the rover operations team, seated adjacent to the Rover Driver console position. RT Sci ensures proper execution of the current tactical plan, including traverses and area of interest mapping. RT Sci can also request rover motion in real time based on a given tactical plan. RT Sci monitors real-time science data during traverses and area of interest maps (AIMs), and can request a rover stop based on real-time assessment of instrument data. In this case, RT Sci reports a requested stop to the science operations team (via Sci Comm), and can recommend transitions between rover modes (see Section 2.4). RT Sci also reports other rover activity changes (such as unforeseen terrain obstacles, communications dropouts, etc.) to the Science Team in full simulation mode via Sci Comm.

2.3.2.4. Rover Driver. The Rover Driver position has the responsibility to initiate and monitor rover motion. The Rover Driver initially follows a pre-planned traverse but can also execute rover operations at the request of RT Science.

2.3.2.5. Rover Systems. The Rover Systems console position monitors the state of health of all Rover Systems, reports off nominal system conditions and performs initial diagnoses, periodically estimates resources (such as power) status against allocations, and reports any excess or shortage of resources required to complete the current tactical plan.

2.3.2.6. E-Stop/Joystick. The Emergency-Stop/Joystick position was unique to the MVP field campaign and would not be employed on a lunar mission. In case of any unforeseen danger to the rover vehicle, the E-Stop Operator accompanies the rover in the field on the traverse plan and can immediately halt all rover activity. If needed, the E-Stop/Joystick position also allows the operator to manually move the terrestrial rover via joystick control out of any dangerous location which could cause harm to the vehicle and/or payload.

2.3.2.7. Rover Data. The Rover Data position was unique to the MVP field campaign and would not be employed on a lunar mission. The Data position was responsible for end-to-end network connectivity and data integrity between the Mojave Desert field site and NASA Ames

Research Center (Science Operations Center). The Data console position monitors and resolves any Mojave-NASA connectivity issues, monitors the bandwidth utilization and updates router configurations when necessary, and monitors and troubleshoots any instrument to Rover Data interfaces.

2.4. Rover modes

The rover primarily operates in two modes, (1) prospecting and (2) detailed investigation. Each mode is described below.

2.4.1. Prospecting mode

Prospecting mode is used to survey wide areas and broad features (on the order of a km wide) such as slopes or contacts visible in satellite imagery. Prospecting plans take into account the satellite imagery, a DEM (Digital Elevation Model), initial traversability assessment based on rover navigation limitations from the rover operations team, and science goals. Rover plans for prospecting mode are made in advance and executed during the field test, and can be edited by the Science Team in response to general trends observed during operations. NSS, NIRVSS, and the camera system operate during prospecting mode.

2.4.2. Detailed investigation mode

Detailed investigation mode is used to seek out the boundaries or map any high spatial variability observed during prospecting. Typically the Science Team can decide to enter a detailed investigation mode upon observing a higher level of volatiles in the subsurface and/or surface during prospecting mode. In the Mojave Desert, as on the Moon, the water distribution is unknown a priori, and thus the Science Team must be flexible and in real-time adapt regarding the methodology of mapping the native distribution of water. Generalized rover plans can be developed prior to the mission (e.g., a spiral or raster traverse pattern at various spatial scales), but rover plans for detailed investigation mode may be altered in real time in response to real time observations and discoveries. This method of operations provides a realistic driver for assessing the utility of xGDS for Real Time Science, situational awareness, and operational efficacy in a setting and an operations concept that approximate lunar polar volatile prospecting.

2.5. MVP software architecture

The operations software used to enable the MVP field campaign was the Exploration Ground Data System (xGDS). xGDS is a set of tools for Science Teams and mission operators to plan, monitor, and document science operations, and to organize mission data to make it easier to search, browse, and explore. xGDS is implemented as a set of web services to facilitate collaboration by a distributed team and provide a central repository of information (Deans et al., 2015).

xGDS is designed to support four mission phases: (1) planning, (2) monitoring, (3) archiving, and (4) exploring. Planning begins with a priori map information such as remote sensing data, known operational hazards or constraints, and targets of interest. xGDS enables teams to create and share map content and collaboratively edit plans. For MVP, the Science Team used xGDS in planning mode to develop traverse paths to indicate where the rover should drive and collect data within the Mojave Desert (Fig. 6a). Data monitoring is accomplished via map- and plot-based tools to visualize payload telemetry and vehicle position in real-time, and also includes real-time and post hoc documentation and annotation. The MVP Science Team actively monitored payload and vehicle telemetry data in real time and used this information to make real-time operational decisions. All MVP team members had access to the real-time data simultaneously through xGDS. xGDS analysis tools for MVP were focused on the NSS and NIRVSS Science instruments. NSS data was ingested by xGDS and displayed as both time-dependent strip charts of neutron counts as well as georeferenced color-coded rover paths to indicate neutron counts as a function of location. NIRVSS data was displayed as both time-dependent strip charts of water band depths as well as georeferenced color-coded rover paths to indicate water band depths as a function of location. xGDS archiving tools ingest telemetry in real-time, reducing data to more meaningful or efficient representations and organizing it into searchable databases. The xGDS archiving capability was used during MVP to create meaningful representations of raw data such as more intuitive representations of volumetric hydrogen abundance from the neutron spectrometer or relative amounts of surface-bound water as measured by the near-infrared spectrometer onboard the rover. xGDS also allows users to explore data later which requires the ability to quickly determine what data was collected, where and when it was collected, and search for particular types of data (Deans et al., 2015).

MVP also used the Playbook software to enable robust timelining and scheduling of mission activities. Playbook is a mobile, web-based timeline viewer and execution software aid that has been field tested in a variety of field science campaigns (Marquez et al., 2013) and utilized for in-flight space operations. MVP operations utilized several key aspects of Playbook including visualization for mission activity timelines and tracking between planned and executed operations. As shown in Fig. 2, Playbook provided a visual representation of mission activities as well as their associated start and stop times as well as durations for key mission components during MVP operations.

3. Results

MVP demonstrated that real-time rover operations is a new concept of operations for planetary missions which

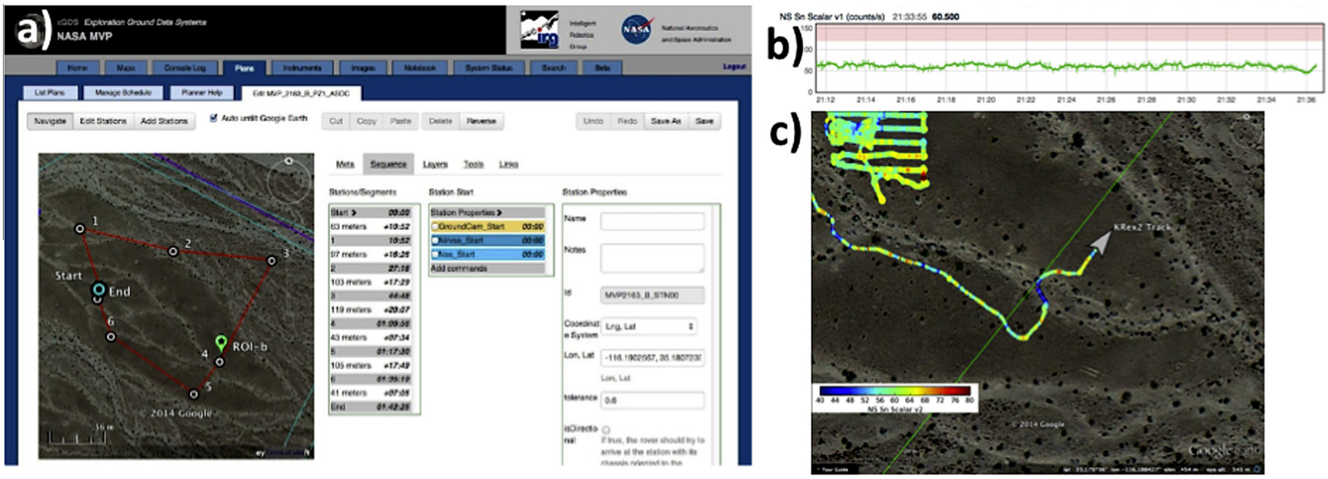

Fig. 6. (a) Exploration Ground Data System (xGDS) planner shows a map view including lists of waypoints and activities (from Deans et al. (2015)). (b) Exploration Ground Data System (xGDS) strip chart showing neutron counts as a function of time as detected by the rover-mounted neutron spectrometer. (c) Exploration Ground Data System (xGDS) raster map showing neutron counts as a function of geographic location as detected by the rover-mounted neutron spectrometer. This section of traverse path is located in PZ-1 (see Fig. 4b).

requires new methods of operations and support tools. Initial findings are listed below for the topics of console architecture, xGDS, communications, and decision making based on the MVP field deployment which have direct relevance for a future lunar polar rover mission such as Resource Prospector. We note that although a lunar polar rover mission would operate continuously for multiple days, MVP was executed using one shift of personnel during the work day. Thus issues of shift handover with multiple crews performing operations each day were not addressed through the MVP campaign.

3.1. Console architecture

The console architecture within the Science Operations Center must be optimized for conducting real-time mission operations. Science interests must be adequately represented within the Operations Center, and dedicated console positions for monitoring each of the instrument payload elements (NIRVSS, NSS, Camera) are essential. A separate Science Lead for strategic planning (SOM) and tactical planning (Sci Lead) is critical since the Sci Lead tends to become engrossed in the technical details of tactical planning while the SOM can maintain a broad view of the mission operations and ensure completion of the formal mission goals and objectives. Science discussions in the SOC were relatively informal and occurred in real-time as the data and telemetry was fed to the SOC via xGDS. When an area of interest was noted by the SOC, the Sci Lead typically led a discussion with the SOC members to determine the level of interest and whether or not to alter the existing traverse plans. Ultimately the SOM had final authority over all operational decisions.

A dedicated Sci Comm position is necessary as well to minimize cross-talk and auditory confusion for relaying information between the Science Operations Center and the Rover Operations Center. The Traverse Planner position is optimized when filled by a trained scientist since this person is responsible for synthesizing the information learned from the Rover Data as well as the intentions of the Science Team in creating updated rover traverse plans. The Timeliner and Stenographer need not be fully trained scientists, but should be literate in the science to follow and understand the mission activities. In addition, the Timeliner and Stenographer should have ample training and experience using their respective software packages in order to ensure rapid recording and updating of information as the mission progresses.

The utility of a Science Backroom is notably different from the task functions of the Science Operations Center. The Science Backroom is beneficial for performing more detailed data analysis and/or targeted tasks as requested from the Science Operations Center. However, the Backroom typically lacks adequate situational awareness to participate meaningfully in real-time operational decisions, primarily because the Backroom members are not actively following the detailed mission activities and instead are focused on detailed science data analysis. The Science Backroom has the ability to tease out additional information that the Science Operations Center often cannot due to lack of dedicated data analysis time, and thus a debrief from the Science Backroom at the end of each shift is useful and can help guide the activities for the remainder of the mission. We note that since MVP conducted operations during the daytime only, shift handovers were not addressed and the timing of Science Backroom debriefs was at the end of day for MVP due to logistical constraints.

3.2. Ground data systems

Real-time Rover Data monitoring by the Science Team to inform real-time decision making requires specialized ground data systems, and the capabilities of xGDS were critical for enabling this mission architecture. The Science Team requires a real-time ability to respond to science data (e.g., update traverse plans, modify rover activities, etc.), and the xGDS platform provided these capabilities in a seamless manner since multiple science functions (traverse planning, data monitoring, data archiving, note taking, etc.) were all performed with the xGDS platform.

A key development for MVP was specialized user interfaces for monitoring the specific data products of the MVP (and RP) prospecting instruments, namely the NIRVSS and NSS. As shown in Fig. 6b, a time-dependent strip chart was developed to display neutron counts in real time. Predetermined thresholds were also developed to easily identify when a potentially interesting region was traversed based on the neutron data. Likewise, specialized strip charts were developed for the NIRVSS data to display several water absorption band depths in real time. These displays allowed the NSS and NIRVSS Science Team members to quickly and easily monitor simple data products to rapidly assimilate the data as measurements were collected. The xGDS developers also integrated a georeferenced method for displaying the prospecting data. Fig. 6c shows a raster map with NSS data displayed to indicate the locations where various levels of neutron counts were detected (similar raster maps were available for the NIRVSS data). The Science Team had the ability to monitor the data in either strip chart or raster map mode, which allows flexibility depending on the data returned and the needs of the Science Team.

The xGDS platform also included the ability to archive Rover Data. This data could then be searched and accessed for subsequent data analysis. The capability to archive the data is necessary for Science follow-up to test hypotheses, revisit sites, and inform operations. Easy and rapid access to the raw data allowed the Science Team to perform additional processing and gain a deeper understanding of the data, which thereby informed science discussions, hypotheses, and ultimately operations. The archived data was also used during the MVP operations by the Science Backroom to target specific datasets and follow up on the most interesting science data to inform upcoming mission operations.

The MVP field campaign also highlighted the need for integrating timelining capabilities within the planning and execution modes of xGDS. During MVP, the Playbook timelining software was used to assess the availability of time as a resource for planning, replanning, and execution of traverse plans developed within xGDS. However, the timing data integration between xGDS and Playbook was not automatic. MVP highlighted the need for integrated software tools that are required to enable the unique nature of real-time operations for terrestrial missions such as MVP and planetary missions such as RP. Advanced analysis tools have the potential to increase the efficiency of the real-time operations. Additional developments in the decision-making tools could likely also further increase the efficiency of operations, and this is a topic that warrants further research and testing.

3.3. Communications

Communications protocols within the operations architecture are required to facilitate real-time decision making. The MVP field campaign provided a high fidelity test of communications architectures which must allow for required information to be provided to requisite console positions, but the information relayed also must not be overwhelming to cause too much confusion and lack of focus in order to accomplish each individual console task. MVP demonstrated the need for multiple communications voice loops such that only relevant parties were listening and/or talking on each loop. MVP ultimately utilized four voice loops for MVP operations relevant to a lunar mission, and then used two voice loops for communications specific to the terrestrial field test. The primary voice loops relevant to both MVP and an RP mission included MVP-OPS (MVP-Operations), ROVER-COMM (Rover Communication), SOC-COORD (Science Operations Center Coordination), and ROVER-COORD (Rover Coordination). MVP-OPS was the primary operations voice loop which provided communications among the SOM, Sci Lead, Sci Comm, RT Sci, and Rover Lead. This loop provided situational awareness about the science for the rover team, and vice versa. The ROVER-COMM voice loop was used for real-time coordination between the science and rover teams. The SOC-COORD loop was used for internal Science Operations Center discussion, and the ROVER-COORD loop was used for internal rover operations discussion. The two voice loops specific to the MVP terrestrial test included SIM-COORD (Simulation Coordination), which was used to coordinate between the Test Director at NASA Ames and the rover field team and E-STOP (Emergency Stop) which was for conversation between the field-based rover team and the E-STOP Operator who accompanied the rover during its traverses. Table 1 lists the console positions and associated voice loops (talk and/or listen modes).

Also, MVP has demonstrated that the RT Sci position must be in direct communication the Rover Driver to enable efficient real-time operations. This finding was also highlighted during a previous rover field campaign in Hawaii in 2012 (Heldmann et al., 2015b). The RT Sci operator is a scientist with an intimate understanding of the scientific objectives of the mission as well as the ability to rapidly synthesize incoming prospecting data and coordinate with the Science Operations Center. RT Sci must thus have the ability to affect rover operations in real-time, and the rapid nature of this operations turn-around necessitates a direct line of communication with the Rover Navigation operator.

Table 1
Matrix showing console positions for the MVP Science Operations Center and Rover Operations Center as well as assigned voice loops to talk and/or listen. Entries designated as "listen" indicate the console staffer should only listen to activities on this voice loop for mission information relevant to his/her assigned duties. Entries designated as "talk" indicate the console position has the authority to speak on the loop and should listen to transmissions as well.

Console position	Voice loops MVP-OPS	SOC-COORD	ROVER-COMM	ROVER-COORD	SIM-COORD	E-STOP
Science Operations Center						
Science Ops Manager	Talk	Talk	Listen		Talk	Listen
Science Lead	Talk	Talk	Listen			
Science Communicator	Talk	Talk	Talk			
NIRVSS Science		Talk				
NSS Ccience		Talk				
Ground Camera Science		Talk				
Traverse Planner		Talk				
Timeliner		Talk				
Stenographer		Talk				
Test Director	Listen				Talk	Talk
Rover Operations Center						
Rover Lead	Talk	Listen	Talk	Talk	Talk	Talk
Real Time Science	Talk	Listen	Talk	Talk	Talk	
Rover Driver	Listen		Talk	Talk	Talk	Talk
Rover Systems				Talk		
Rover Data						
E-Stop Operator					Listen	Talk

3.4. Decision making

The MVP field test has demonstrated the need for significant flexibility to change operations plans during the mission. Flexibility must remain within the daily operations plans to react to unexpected/interesting data and/or situations as warranted. Data was downloaded to the Science Team via xGDS within a matter of seconds after the data was collected by the rover payload. The Science Operations Center personnel monitored this data as it was received, and discussions of the data amongst the SOC members occurred instantly. Typically the SOC made a decision to halt rover operations within a few minutes of observing an interesting data signal. This decision time is important because the rover is continuously moving, and in order to stop and assess a particular region in more detail, the SOC needed to make the call to halt the rover before the rover had traversed too far beyond the point of interest. The mission architecture must be designed such that the Science Team has sufficient operational decision making authority. To meet this need, the MVP field deployment further demonstrated the need for the RT Sci position to have authority to request immediate changes to the rover tactical plan (Heldmann et al., 2015b). A priori criteria should be established to guide real-time operations (e.g., predetermined thresholds for surface or subsurface water content which may instigate a rover halt), but the Science Team also must have authority to deviate from nominal plan based on situational awareness and experience gained during the course of the mission. For example, specific metrics were used to determine when deviation from the preplanned traverse plans were acceptable. Following Heldmann et al. (2015a, 2015b), if both the near infrared spectrometer (NIRVSS) and neutron spectrometer (NSS) indicated a positive signal for volatiles, the Science Team could recommend that the rover stop in its traverse and performed a more detailed survey of the region since this would represent a high priority volatiles target of interest. If only the neutron spectrometer signal was positive (indicative of volumetric hydrogen) or the near infrared signal was positive, the Science Team could also recommend stopping the planned traverse if the region was deemed interesting in the context of the scientific understanding of the terrain at that point. Under these scenarios, deviation from the pre-planned traverse paths was primarily to enable real-time science as opposed to executing the pre-planned spatial mapping plans. To enable robust decision making, the Science Team must also plan time to ingest and synthesize the results of the ongoing data collection from the rover, and must work to optimize personnel time spent on both tactical and long-term strategic planning.

4. Conclusions

The MVP mission was specifically designed to serve as an analog for the RP mission. However, multiple mission variables such as changing mission requirements, rover capabilities, roving speed, remote sensing data resolution, ability to analyze samples while roving, etc., could affect multiple mission parameters such as team size, console roles, etc. These permutations were beyond the scope of MVP but could be addressed in future field campaigns.

Through this investigation, the MVP field mission has matured robotic in situ instruments and concepts of instrument operations, improved ground software tools for Real Time Science, and carried out publishable research on the water cycle and its connection to geomorphology and mineralogy in desert environments (Elphic et al., 2015b). In particular, MVP has provided key insights into the realms of mission console architecture, ground data systems, communications, and decision making authority, which all affect mission design for future lunar missions. The lessons learned from the MVP deployment have direct relevance to future lunar polar volatiles prospecting missions such as NASA's Resource Prospector. The utility of the MVP field campaign demonstrates the value of relevant field campaigns with targeted objectives to address and test key aspects of various mission design parameters to optimize the efficiency and productivity of future space missions.

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References

Andrews, D., Colaprete, A., Quinn, J., Chavers, D., Picard, M., 2014. Introducing the resource prospector (RP) mission. AIAA SPACE 2014-4378, San Diego, CA.

Arnold, J.R., 1979. Ice in the lunar polar regions. J. Geophys. Res. 84.

Beyer, R.A., Cockrell, J., Colaprete, A., Fong, T., Elphic, R., Heldmann, J., Pedersen, L., 2011. Feasibility and definition of a lunar polar volatiles prospecting mission. In: Lunar and Planetary Science Conference. Abstract #2735.

Brown, D.E., Lowe, E.H., Pase, E.P., 1980. Digitized classification for ecosystems with an illustrated summary of the vegetation of North America. USDA Forest Service (General Technical Report) RM-73.

Butler, B.J., 1997. The migration of volatiles on the surfaces of Mercury and the Moon. J. Geophys. Res. 102.

Campbell, D.B. et al., 2003. Radar imaging of the lunar poles. Nature 426.

Campbell, D.B., Campbell, B.A., Carter, L.M., Margot, J.L., Stacy, N.J.S., 2006. No evidence for thick deposits of ice at the lunar south pole. Nature 443.

Clark, R.N., 2009. Detection of adsorbed water and hydroxyl on the Moon. Science 326. http://dx.doi.org/10.1126/science.1178105.

Colaprete, A., 2014. The Resource Prospector expedition. NASA SSERVI Exploration Science Forum, Moffett Field, CA.

Colaprete, A., Schultz, P., Heldmann, J.L., Shirley, M., Ennico, K., Hermalyn, B., Wooden, D., Marshall, W., Ricco, A., Elphic, R.C., Goldstein, D., Summy, D., Bart, G., Asphaug, E., Korycansky, D., Landis, D., Sollitt, L., 2010. The detection of water within the LCROSS ejecta plume. Science 330. http://dx.doi.org/10.1126/science.1186986.

Crider, D.H., Vondrak, R.R., 2003. Space weathering effects on lunar cold trap deposits. J. Geophys. Res. 108, 3845–3862.

Deans, M.C., Lees, D.S., Cohen, T.E., Lee, Y.J., Smith, T., Wolfe, S.R., Heldmann, J.L., Colaprete, A.C., Elphic, R.E., Lim, D., 2015. Tools for enabling real time volatile prospecting with surface rovers. In: Lunar and Planetary Science Conference. Abstract #2895.

Elphic, R.C., Eke, V.R., Teodoro, L.F.A., Lawrence, D.J., Bussey, D.B.J., 2007a. Models of the distribution and abundance of hydrogen at the lunar south pole. Geophys. Res. Lett. 34.

Elphic, R., Kobayashi, L., Allan, M., Bualat, M., Deans, M., Fong, T.W., Lee, S., To, V., Utz, H., 2007b. Enabling exploration: robotic site surveys and prospecting for hydrogen. In: Workshop on Enabling Exploration: The Lunar Outpost and Beyond. LEAG. Abstract #3046.

Elphic, R.C., Chu, P., Hahn, S., James, M.R., Lawrence, D.J., Prettyman, T.H., Johnson, J.B., Podgorney, R.K., 2008a. Surface and downhole prospecting tools for planetary exploration: tests of neutron and gamma ray probes. Astrobiology 8 (3), 639–652. http://dx.doi.org/10.1089/ast.2007.0163.

Elphic, R., Utz, H., Bualat, M., Deans, M., Fong, T.W., et al., 2008b. Preliminary results of hydrogen prospecting with a planetary rover. In: Lunar and Planetary Science Conference. Abstract #2400.

Elphic, R.C., Heldmann, J.L., Marinova, M.M., Colaprete, A., Fritzler, E.L., McMurray, R.E., Morse, S., Roush, T.L., Stoker, C.R., Deans, M.C., Smith, T.F., 2015a. Simulated real-time lunar volatiles prospecting with a rover-borne neutron spectrometer. Adv. Space Res. 55, 2438–2450.

Elphic, R.C., Heldmann, J.L., Colaprete, A.C., Hunt, D.R., Deans, M.C., Lim, D.S., Foil, G., Fong, T.and the MVP Science Team, 2015b. Neutron spectrometer prospecting during the Mojave Volatiles Project field test. In: Lunar and Planetary Science Conference. Abstract #1832.

Feldman, W.C. et al., 1998. Fluxes of fast and epithermal neutrons from lunar prospector: evidence for water ice at the lunar poles. Science 281.

Feldman, W.C., Lawrence, D.J., Elphic, R.C., Vaniman, D.T., Thomsen, D.R., Barraclough, B.L., Maurice, S., Binder, A.B., 2000. Chemical information content of lunar thermal and epithermal neutrons. J. Geophys. Res. 105.

Feldman, W.C., Maurice, S., Lawrence, D.J., Little, R.C., Lawson, S.L., Gasnault, O., Wiens, R.C., Barraclough, B.L., Elphic, R.C., Prettyman, T.H., Steinberg, J.T., Binder, A.B., 2001. Evidence for water ice near the lunar poles. J. Geophys. Res. 106.

Fristad, K., Bussey, B., Robinson, M., Spudis, P., 2004. Ideal landing sites near the lunar poles. In: Lunar and Planetary Science Conference. Abstract #1582.

Heldmann, J.L., Elphic, R.C., Colaprete, A.C., Fong, T., Pedersen, L., Beyer, R., Cockrell, J., 2012. Feasibility and definition of a lunar polar volatiles prospecting mission. In: Global Space Exploration Conference. IAF.

Heldmann, J.L., Colaprete, A., Cook, A., Roush, T., Deans, M., Elphic, R., Lim, D., Skok, J.R., Button, N.E., Karunatillake, S., Garcia, G., 2015a. Mojave volatiles prospector (MVP): science and operations results from a lunar polar rover analog field campaign. In: Lunar and Planetary Science Conference. Abstract #2165.

Heldmann, J.L., Colaprete, A.C., Elphic, R.E., Mattes, G., Ennico, K., Fritzler, E., Marinova, M., McMurray, R., Morse, S., Roush, T., Stoker, C.R., 2015b. Real-time science operations to support a lunar polar volatiles rover mission. Adv. Space Res. 55, 2427–2437.

Kring, D., Rademacher, J., 2007. Initiating the surface ops phase of the lunar exploration architecture with robotic landers and rovers. In: Lunar and Planetary Science Conference. Abstract #1595.

Lawrence, D.J., Feldman, W.C., Elphic, R.C., Hagerty, J.J., Maurice, S., McKinney, G.W., Prettyman, T.H., 2006. Improved modeling of lunar prospector neutron spectrometer data: implications for hydrogen deposits at the lunar poles. J. Geophys. Res. 111.

Marquez, J., Pyrzak, G., Hashemi, S., Ahmed, S., McMillin, K., Medwid, J., Chen, D., Hurtle, E., 2013. Supporting real-time operations and execution through timeline and scheduling aids, In: 43rd International Conference on Environmental Systems. http://dx.doi.org/10.2514/6.2013-3519.

McFadden, L.D., Wells, S.G., Dohrenwend, J.C., 1986. Influences of quaternary climatic changes on processes of soil development on desert loess deposits of the Cima Volcanic Field, California. Catena 13, 361–389.

Mitrofanov, I. et al., 2010. Hydrogen mapping of the lunar south pole using the LRO neutron detector experiment LEND. Science 330, 483–486.

Mitrofanov, I. et al., 2012. Testing polar spots of water-rich permafrost on the Moon: LEND observations onboard LRO. J. Geophys. Res. http://dx.doi.org/10.1029/2011JE00395.

Nozette, S., Lichtenberg, C.L., Spudis, P., Bonner, R., Ort, W., Malaret, E., Robinson, M., Shoemaker, E.M., 1996. The Clemenite bistatic radar experiment. Science 274, 1495–1498.

Nozette, S., Spudis, P.D., et al., 2001. Integration of lunar polar remote-sensing data sets: evidence for ice at the lunar south pole. J. Geophys. Res. 106.

Paige, D.A. et al., 2010. Diviner lunar radiometer observations of cold traps in the Moon's south polar region. Science 330. http://dx.doi.org/10.1126/science.1187726.

Pieters, C. et al., 2009. Character and spatial distribution of OH/H_2O on the surface of the Moon as seen by M3 on Chandrayaan-1. Science 326. http://dx.doi.org/10.1126/science.1178658.

Plescia, J., Spudis, P., Bussey, B., 2008. A robotic mission strategy for choosing an ISRU prospect and process. In: Space Resources Roundtable VIII. Abstract #1018.

Roush, T., Colaprete, A.C., Elphic, R., Ennico-Smith, K., Heldmann, J. L., Stoker, C., Marinova, M., McMurray, R., Fritzler, E., Morse, S., 2015. In situ resource utilization (ISRU) field expedition 2012: near infrared volatiles spectrometer system (NIRVSS) science measurements compared to site knowledge. Adv. Space Res. 55, 2451–2456.

Sanders, G., Larson, W.E., 2015. Final review of analog field campaigns for in situ resource utilization technology and capability maturation. Adv. Space Res. 55, 2381–2404.

Stacy, N., Campbell, D.B., Ford, P.G., 1997. Arecibo radar mapping of the lunar poles. Science 276.

Sunshine, J.M., Farnham, T.L., Feaga, L.M., Groussin, O., Merlin, F., Milliken, R.E., A'Hearn, M.F., 2009. Temporal and spatial variability of lunar hydration as observed by the deep impact spacecraft. Science 326. http://dx.doi.org/10.1126/science.1179788.

Vasavada, A.R., Paige, D.A., Wood, S.E., 1999. Near-surface temperatures on Mercury and the Moon and the stability of polar ice deposits. Icarus 141.

Watson, K., Murray, B., Brown, H., 1961. On the possible presence of ice on the Moon. J. Geophys. Res. 66.

Webb, R.H., 2002. Recovery of severely compacted soils in the Mojave Desert, California, USA. Arid Land Res. Manage. 16, 291–305.