INTERNATIONAL ACADEMY OF ASTRONAUTICS
10th IAA SYMPOSIUM ON THE FUTURE OF SPACE EXPLORATION: TOWARDS THE MOON VILLAGE AND BEYOND

Torino, Italy, June 27-29, 2017

SCIENCE AND EXPLORATION AT THE MOON AND MARS ENABLED BY SURFACE TELEROBOTICS

Jack O. Burns
University of Colorado Boulder
jack.burns@colorado.edu

Terry Fong
NASA Ames Research Center
terry.fong@nasa.gov

David A. Kring
Lunar and Planetary Institute
kring@lpi.usra.edu

William D. Pratt and Timothy Cichan
Lockheed Martin Space Systems Company
william.d.pratt@lmco.com, timothy.cichan@lmco.com

Abstract: NASA/ESA are preparing a series of Exploration Missions using Orion and additional infrastructure at a Deep Space Gateway in cis-lunar space. This will provide an opportunity for science and exploration from the lunar farside facilitated by surface telerobotics. We describe several precursor telepresence experiments, using the ISS and a student-built rover, which are laying the groundwork for teleoperation of rovers on Moon and eventually Mars. We describe exciting near-term science that can be conducted from the lunar farside with teleoperated rovers including an astronaut-assisted sample return, a high priority from the U.S. Planetary Sciences Decadal Survey, and the deployment of a low frequency radio telescope array to observe the first stars and galaxies (Cosmic Dawn), as described in NASA's Astrophysics Roadmap.

Keywords: Surface Telerobotics, Cosmic Dawn, Orion Crew Vehicle, Deep Space Gateway

1. INTRODUCTION

In the next few years, NASA's SLS will launch the Orion crew vehicle including ESA's European Service Module into lunar orbit where we will begin human exploration beyond LEO for the first time in half a century. A series of Exploration Missions are planned for cis-lunar space to evaluate crew health and spacecraft performance in deep space in order to prepare for long duration missions to Mars. In addition, NASA appears likely to place a Habitat module forming a "Deep Space Gateway" (DSG) at a location such as the Earth-Moon L2 Lagrange Point ($\approx$65,000 km above the lunar farside). The DSG will include a propulsion system that would support transfer between lunar orbits. Orion would dock at the DSG and permit extended stays of several months. In the future, the DSG could also provide a docking station for a reusable lander (possibly provided by international or commercial partners) which would then offer astronaut access to both the near and far sides of the Moon's surface.

During the early phases of development of infrastructure near the Moon, there is an exciting opportunity to begin a new era of space science and exploration enabled by telepresence. Surface telerobotics (i.e., astronauts in orbit operating rovers or other robotic surface assets "at a distance") can be used to collect unique geological samples and to deploy a low frequency radio telescope. Precursor experiments are setting the stage for teleoperation from lunar orbit. Student-focused laboratory and field trials are beginning to provide requirements on bandwidth, video frame rates, and latency for effective scientific exploration on the lunar surface. A NASA-funded experiment aboard the International Space Station (serving as a proxy for Orion/DSG) has successfully operated NASA's K10 planetary rover over a simulated lunar terrain at the NASA Ames Research Center to deploy an engineering prototype of a radio telescope array. ESA subsequently conducted a similar experiment to operate a ground-based rover from the ISS.

Forefront science (e.g., as described in the U.S. National Academy Decadal Surveys) can be conducted from the lunar farside using surface telerobotics as a harbinger for returning humans to the Moon. For example, a teleoperated rover will enable the collection of multiple rock samples from the Moon's South Pole-Aitken (SPA) basin, as recommended by the U.S. Planetary Sciences Decadal Survey and the NRC-2007 [7] report. As a second example, this mission could deploy a low frequency radio telescope array to observe the redshifted 21-cm power spectrum originating from structure within the intergalactic medium surrounding the first stars and galaxies; these observations help to fulfill recommendations from the U.S. Astrophysics Decadal Survey and NASA's Astrophysics Roadmap (observing the "Cosmic Dawn").

Such surface telerobotics support "off-board" autonomy and prepare for human Mars missions. These cis-lunar experiments will train astronaut crews to virtually explore the surface of Mars from orbit using robots as avatars.

We begin this paper in Section 2 with an elaboration of the capabilities of Orion and a Deep Space Gateway in cis-lunar space that will facilitate surface telerobotics experiments on the lunar farside. In Section 3, we describe precursor experiments using the ISS and a student-built teleoperated rover that are helping to define requirements for cis-lunar operations. In Section 4, science from the lunar farside expedited by surface telerobotics is described including astronaut-assisted sample return and low radio frequency observations of Cosmic Dawn.

2. EXPLORATION WITH ORION AND A DEEP SPACE GATEWAY

2.1 The Deep Space Gateway as Supporting Infrastructure for Lunar Surface Telerobotics

The Deep Space Gateway in Figure 1 will be used to achieve lunar science objectives while simultaneously laying the groundwork for future deep space missions. Astronauts will be on-board the DSG for up to 60 days initially each year. The DSG's capability to support much longer durations will increase with each mission (perhaps up to 180 days with increased cargo capacity and increased water recycling in the life support system). During this period of time, the crew will be able to perform scientific experiments in the DSG and also support other lunar science from cis-lunar space. For the remainder of the year, the DSG will remain uncrewed, but with opportunities to continue lunar science even without the crew present. Importantly, the DSG will remain as a communication relay to farside surface assets. There are several key lunar farside science objectives discussed in this paper, which have been identified by planetary science and astrophysics communities as top priorities and can be supported through use of the DSG.

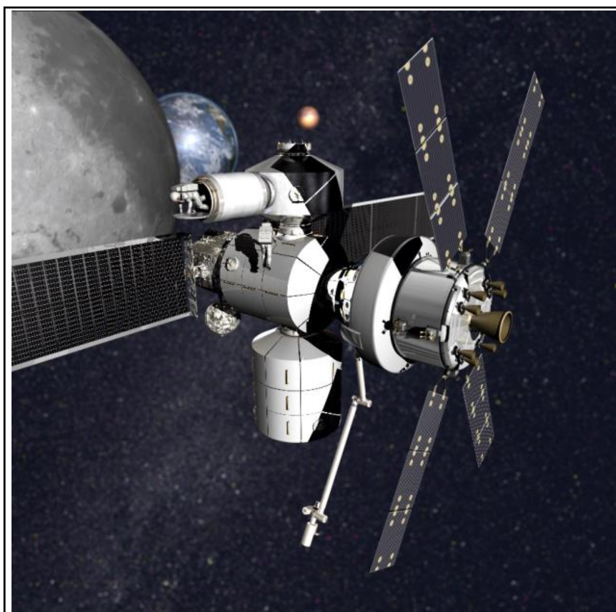

Figure 1. Lockheed Martin's Deep Space Gateway concept supports lunar science objectives and serves as a state-of-the-art telerobotics platform.

The DSG communications architecture is designed to exchange commands and telemetry via space to ground, space to space, and space to lunar surface links. The DSG communications system has deep space heritage from planetary spacecraft, and Orion to meet the various communication needs and utilizes channels across the frequency spectrum including X-band, S-band and optical communication. While the DSG is in lunar orbit without Orion, commands and telemetry will be exchanged over an X-band link with the Deep Space Network (DSN) via a 2 meter High Gain Antenna (HGA). During rendezvous and proximity operations, DSG will communicate with Orion over S-Band. The DSG will leverage S-Band components developed for Orion to ensure compatibility and affordability. Once docked, data will be exchanged between DSG and Orion via a hardline connection. Information from Orion can be downlinked to the DSN via the DSG's HGA; and vice versa, information from the DSG can be downlinked via Orion's Phased Array Antennas that are part of its S-Band system.

The lunar farside is of scientific interest, but currently no communications architecture exists there to support scientific missions. The DSG can act as a communications relay to any surface or orbital missions, including international missions, and can transmit the data back to scientists on Earth via either the HGA or the optical communication terminal. The science and video data collected by the DSG is most efficiently downlinked using an optical communication system. Optical communication enables a significant increase to downlink bandwidth capability compared to traditional radio frequency (RF) communication, for example NASA's Lunar Laser Communication Demonstration (LLCD) demonstrated a record-breaking Moon to Earth download rate of 622 Mbps.

2.2 The Orion Crew Vehicle

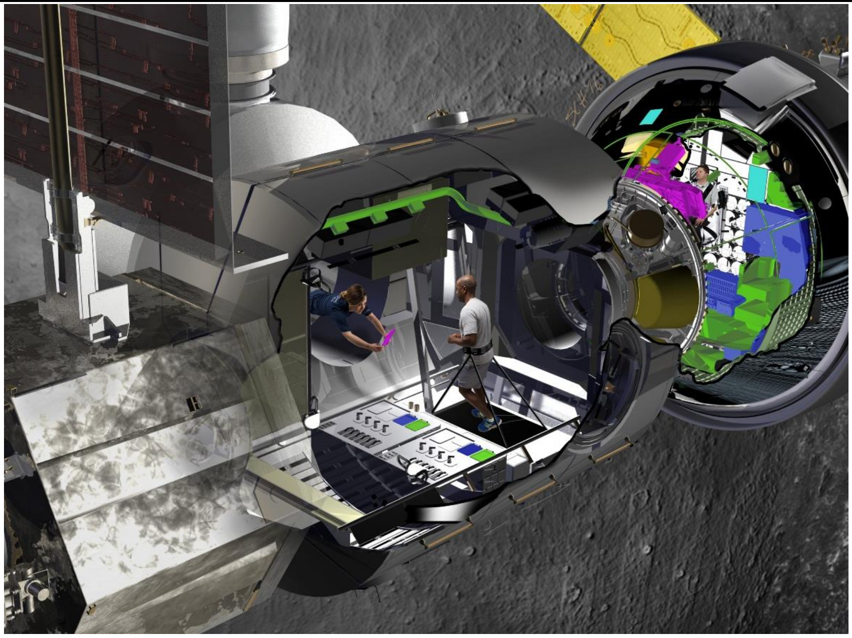

Figure 2. Orion will serve as the command deck of the Deep Space Gateway, providing advanced functionality needed to support human presence.

The most affordable way to send humans to DSG in cis-lunar space in the near term is to leverage NASA's investment in current systems and technologies. Aspects of the avionics, crew interface, life support, power, communication, and navigation systems on Orion can be utilized to minimize duplication and rework on the Deep Space Gateway while providing a safe environment for astronauts to live and work. Figure 2 highlights some of the advanced subsystems on Orion that can be used to increase safety and affordability of the gateway.

Command and Control of Orion was designed to cover critical functionality, functional availability and functional safety to meet key performance requirements. There are four redundant Flight Computer Modules (FCMs) within the two Vehicle Management Computers (VMCs). The FCMs provide a high integrity platform to house software applications. The FCMs have sufficient processing power to perform command and control of Orion as well as the DSG. Utilizing Orion as the command deck when docked with DSG enables a more streamlined approach to the avionics on the DSG. The DSG command and data handling can be more akin to a deep space planetary mission because it relies on the reliability and availability built into Orion.

In the unlikely event that something goes amiss with the primary flight computers on Orion, a dissimilar processing platform with dissimilar flight software is hosted on the Vision Processing Unit (VPU). The VPU provides a hot backup function to the redundant FCMs during critical phases of flight. This capability can also be utilized by astronauts aboard the DSG should emergencies arise in cis-lunar space.

Orion employs a wireless communication system to interface with cameras used to monitor critical events and crew activities. This system is capable of sending commands and receiving telemetry from end systems and is connected to a utility network that interfaces with the ODN. With the use of portable tablets and the Orion wireless communication system, the crew has flexibility to be in any area of the combined Orion/Deep Space Gateway and have insight into the critical systems of the cis-lunar station while having the ability to act on any urgent caution, warning or emergency alerts.

The Orion Displays and Control equipment is the crew interface to its subsystems. The Display Units (DUs) utilize a variety of Display Formats to provide data to the crew for awareness and action when necessary. The Display Format Software Architecture enables streamlined addition of new formats via the Generic Display Engine or for more complex formats via a library of reusable and common graphical elements. This library of graphical elements can be leveraged to facilitate development of unique Formats for the DSG which can be displayed on the Orion DUs or the supplemental wireless tablet. Electronic Procedures have been developed for Orion that allow direct interaction with the Display Formats enabling reduced workload on the Crew. This same methodology can be employed on the DSG, providing the crew more time to accomplish more mission objectives and increase science return.

There is a symbiotic relationship between Orion's Environmental Control and Life Support Systems (ECLSS) and what is needed on the DSG. Utilizing the waste management system and galley with water dispenser on Orion, prevents the need to duplicate those systems on the DSG. Orion's regenerative pressure swing amine beds can simultaneously remove CO_2 and humidity during docked operations, which reduces the load required for the DSG to handle. Additionally, Orion utilizes a regenerative Phase Change Material (PCM) heat exchanger to accommodate peaks of high thermal loads rather than expendable consumables, which may reduce complexity of the DSG/habitat system.

The Orion power system is capable of generating and supplying more power than is required for its on-orbit operations and surplus power can be shared with the DSG to supplement science experiments performed by the crew. The four Orion solar arrays generate about 11kW of power and extend 62 feet when extended. Orion's batteries use small cell packaging technology to ensure crew safety when providing 120V power to the many systems on Orion and this technology can also be leveraged to ensure a safe environment while the crew is onboard the DSG.

3. SURFACE TELEROBOTICS EXPERIMENTS

Since the early 1960's, humans have been exploring space through an on-going series of missions. Many of these missions have involved short-duration, orbital flights (the Space Shuttle, Soyuz, etc). Other orbital missions have focused on long-duration space stations (Mir, Skylab, and the International Space Station). Beyond Earth Orbit, the Apollo missions orbited and landed humans on the Moon.

In planning for future human space exploration, numerous NASA and international study teams have hypothesized that astronauts can efficiently remotely-operate surface robots from a flight vehicle. This concept of operations is seen as a cost-effective method for performing surface EVA activities. Moreover, it is believed that such "surface telerobotics" can enhance and extend human capabilities, enabling astronauts to be telepresent on planetary surfaces in a highly productive manner.

Many assumptions have been made regarding surface telerobotics, including technology maturity, technology gaps, and operational risks. Although many related terrestrial systems exist (e.g., unmanned aerial vehicles), integrating telerobots into human space exploration raises several important questions. What system configurations are effective? Which modes of operation and control are most appropriate? When is it appropriate to rely (or not) on telerobots? How does communications availability, bandwidth, and latency impact productivity (e.g., [1])?

3.1. International Space Station Experiment

During Summer 2013, we conducted initial testing of the "Orion/DSG L2 Farside" mission concept using the International Space Station (ISS) in Low-Earth Orbit as a proxy for the Deep Space Gateway in cis-lunar space

[1]. Over the course of ISS Expedition 36, astronauts Chris Cassidy, Luca Parmitano, and Karen Nyberg on the ISS remotely operated NASA's "K10" planetary rover in the "Roverscape" analogue lunar terrain located at the NASA Ames Research Center. The astronauts used a Space Station Computer (Lenovo Thinkpad laptop), supervisory control (command sequencing with interactive monitoring), teleoperation (discrete commanding), and Ku-band satellite communications to operate K10 for a combined total of 11 hours.

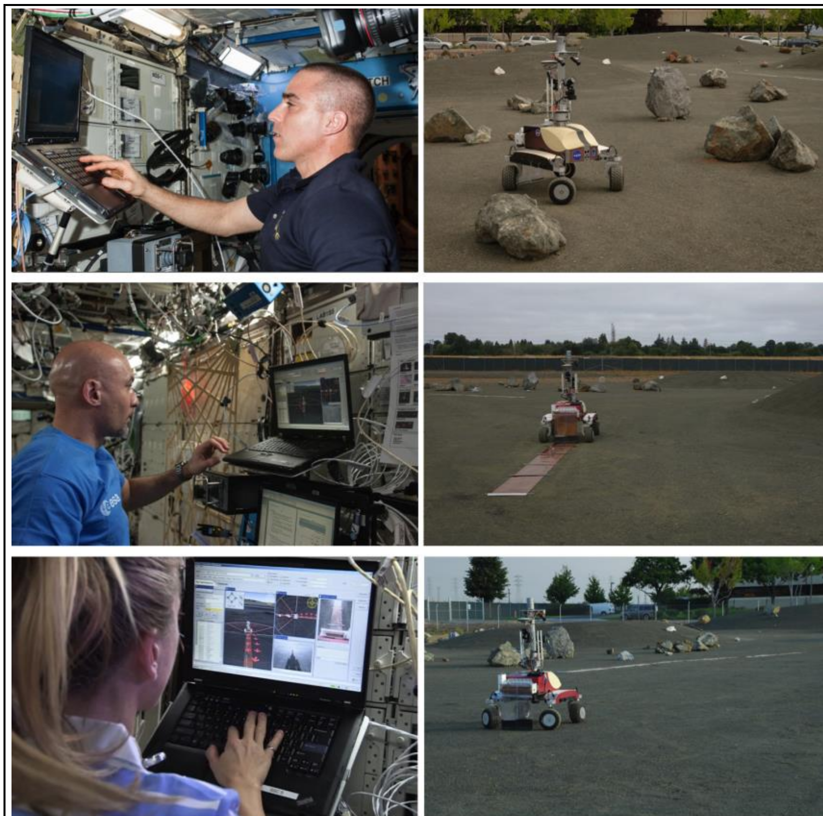

Figure 3. Surface Telerobotics testing. *Top:* site survey of the Roverscape at NASA Ames; *middle:* deploying a simulated lunar telescope antenna; *bottom:* documenting the deployed antenna.

The testing was designed to simulate four mission phases: pre-mission planning, site survey, telescope deployment, and telescope inspection. We performed the pre-mission planning phase using satellite imagery of the test site at a resolution comparable to what is currently available for the Moon and a derived terrain model to select a nominal site for deployment. In addition, the planning team created a set of rover task sequences to survey the site, looking for hazards and obstacles. Since none of the astronauts had prior experience with K10 or the operator interface, each session included an hour of "just in time" training with both. After training, each astronaut remotely operated K10 for approximately two hours.

On June 17, 2013 (Session 1), NASA Astronaut Chris Cassidy remotely operated the K10 rover to survey the Roverscape site (Figure 3, top). The survey data collected with K10 enabled assessment of site characteristics, including obstacles (e.g., large rocks), slopes, and other terrain features. Surface-level survey complements remote sensing data acquired from orbit by providing measurements at resolutions and from viewpoints not achievable from orbit. In particular, K10 provided close-up, oblique views of the locations planned for telescope deployment.

On July 26, 2013 (Session 2), ESA Astronaut Luca Parmitano used K10 to deploy three "arms" of a simulated radio telescope array (Figure 3, middle). Parmitano first executed each task sequence with the deployment device disabled, to verify that the sequence is feasible. He then commanded K10 to perform the actual deployment using rolls of polyimide film as a proxy for a polymide film-based antenna (Section 4.3). The three arms were deployed in a "Y" pattern, which is a possible configuration for a future lunar radio telescope.

Finally, on August 20, 2013 (Session 3), Astronaut Karen Nyberg remotely operated K10 to document the deployed telescope array (Figure 3, bottom). The primary objective of this final phase was to acquire high-resolution images of each antenna arm. These images serve two purposes: (1) in-situ, "as built" document of the deployed array; and (2) source data for locating and analyzing potential flaws (tears, kinks, etc.) that may have occurred during deployment.

Our data analysis [3] indicates that command sequencing with interactive monitoring is an effective strategy for crew-centric surface telerobotics: (1) planetary rover autonomy (especially safeguarded driving) enabled the human-robot team to perform missions safely; (2) the crew maintained good situation awareness with low effort using interactive 3-D visualization of robot state and activity; and (3) rover utilization was consistently in excess of 50% time; and (4) 100% of crew interventions were successful. In addition, we observed that crew workload was consistently low, which suggests that multi-tasking may be possible during telerobotic operations.

We found that supervisory control is a highly effective strategy for crew-centric surface telerobotics. Subjective measurements made with the Bedford Workload Scale (BWS) indicate that task load was low. The BWS provides subjective ratings of workload during (or immediately following) task performance. During Session 1, workload varied on the BWS scale between 2 (low) and 3 (spare capacity for all desired additional tasks). In Session 2, workload was consistently and continuously 2 (low). Finally, during Session 3, workload ranged from 1 (insignificant) to 2 (low).

From SAGAT questionnaires, we determined that all three astronauts were able to maintain a high level of situation awareness (SA) during operations. In particular, we found that each astronaut was able to maintain all three SA levels (perception, comprehension, and projection) more than 67% of the time. From post-test debriefs, we also determined that interactive 3-D visualization of robot state and activity employed in the operator interface was a key contributing factor to achieving high levels of SA. Additionally, because we designed the test sessions to be increasingly difficult (in terms of task sequence complexity, number of contingencies/difficulties encountered, etc.), we expected SA to decrease between Session 1 and 3. The data confirms that this was the case.

The 2013 tests suggest that for future missions where astronauts would operate surface robots from an Earth-Moon L2 halo orbit, or distant retrograde orbit, it is important to design the system and operational protocols to work well with variable quality communications (data rates, latency, availability, etc.). In addition, for deep-space missions, it will also be important to understand how efficiently and effectively a small crew of astronauts can work when operating robots largely independent of mission control support.

Future "Surface Telerobotics" testing with the ISS could be designed to test different mission objectives, such as field geology or sample collection [4]. The ISS presents a highly configurable and unique opportunity to explore mission constraints with a high-fidelity environment for crew. Potential benefits to future missions include: creating optimized crew training techniques and procedures, reducing operational risk and technology gaps, defining preliminary mission requirements, and estimating development and mission cost.

3.2. Student Telerobotics Experiment: The Impact of Video Frame Rate on Exploration Efficiency

Over the past year, a student-led project at the University of Colorado was undertaken to investigate the effects of video frame rate on an operator's ability to explore an unfamiliar environment using low-latency telerobotics [5]. Our hypothesis was that a frame rate threshold exists such that once it is met, exploration efficiency is reduced to a point where operations are no longer effective. Such data will be helpful in the design of the telerobotics systems for Orion/DSG. In order to test our hypothesis, we devised an experiment utilizing

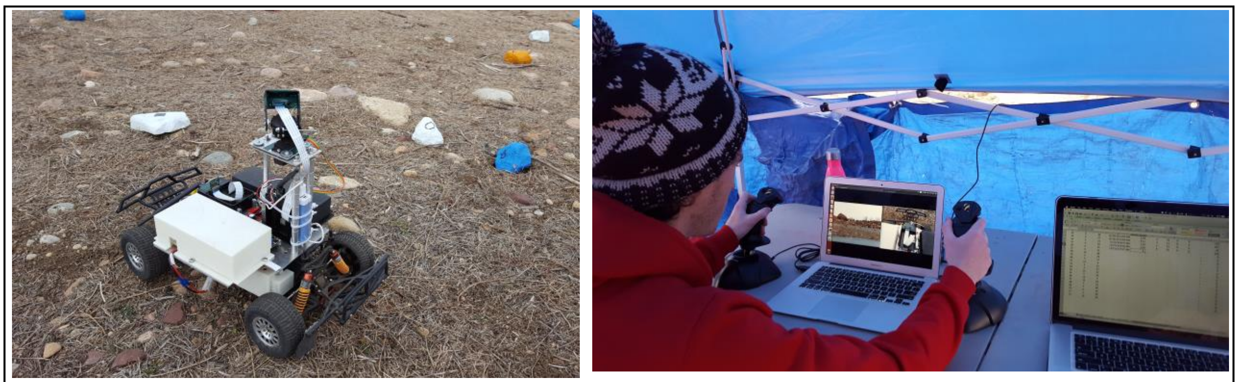

Figure 4. *Left:* The University of Colorado student-built, teleoperated rover and exploration targets (painted stones). *Right:* Operator controlling the rover joysticks ensuring exploration through the rover's twin cameras.

"interesting" exploration target objects, telerobotic operators, and a Telerobotic Simulation System (TSS). The target objects used were painted rocks with various symbols. The TSS consisted of a rover operated by sending joystick input commands via a radio-frequency transmitter/receiver and a suite of software used to adjust the video stream conditions. Pictures illustrating this experiment are shown in Figure 4.

The experiment took place on the University of Colorado campus within a crater-like landscape. Each trial had the operator search for a particular target object, a blue rock with an 'X' for example. Each trial had three possible frame rates: 4, 5, and 6 frames/second. The frame rate of each trial was randomly distributed as well as the target object the operator had to find. In addition to recording the time to discovery for each trial, we also documented the number of times the rover was stuck.

The data analysis began by examining the distribution of times to discovery for the exploration targets. We found this distribution to be non-normal (i.e., non-Gaussian) at the 95% confidence level. This, then, determined the approach for the study of the variance of each frame rate and subsequent post-hoc analyses. Next, we evaluated the mean absolute deviation from the median (ADM) or, effectively, the variance in times to discovery. Considering that our data do not fit a Gaussian distribution, an Analysis of Variance (ANOVA) was performed on the ADM. It was determined that the mean ADM across each frame rate was not equivalent. We then employed a post-hoc analysis to compare the different frame rate groups. We found that 5 and 6 frames/second were indistinguishable from each other while 4 frames/second had a significantly higher mean ADM with 95% certainty.

Finally, we analyzed the mean time to discovery (MTD) with respect to frame rates as shown in Figure 5. We ran an Analysis of Variance (ANOVA) and found that at least one frame rate was statistically different from the others. Again, we used a post-hoc analysis to determine which frame rates were different from one another with respect to the MTD. The 5 and 6 frames/second were found to be indistinguishable from each other while 4 frames/second had a significantly higher MTD with 95% certainty. Thus, we discovered for the parameters of this particular experiment that a threshold of 5 frames/second exists, below which the operational effectiveness for exploration/discovery drops significantly. This result is consistent with experiments from video gaming [5].

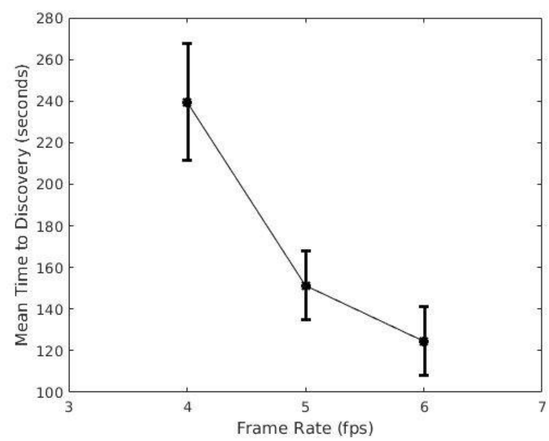

Figure 5. The mean time to discovery (MTD) of target objects versus frame rate for the Colorado teleoperated rover shows a significant degradation, at the 95% confidence level, below 5 frames/ second. The lines between data points illustrate the slope changes in the MTD relationship with frame rate.

4. SCIENCE FROM THE LUNAR FARSIDE

4.2. Human-Assisted Sample Return

If a human-assisted telerobotic sample return mission were developed, where might it land? A global lunar landing site study [6] investigated sites suitable for NRC-2007 [7] science and exploration objectives and determined the highest priority landing site for human-assisted sample return missions, enabled by surface telerobotics, is the Schrödinger impact basin within the South Pole-Aitken impact basin.

The highest priority objective of the NRC-2007 report is to test the lunar cataclysm hypothesis, which suggests the Moon (and, thus, Earth) was severely bombarded by asteroids and comets circa 4 billion years ago. Because that event reshaped the surface of the Moon, may have resurfaced all of the terrestrial planets, and has been implicated in the early evolution of life, it is important to determine the duration of that bombardment. The Schrödinger basin (Figure 6) is the second youngest impact basin on the Moon, while the South Pole-Aitken (SPA) basin is the oldest impact basin on the Moon, so collecting samples produced by both events would bracket the duration of the hypothesized impact cataclysm.

The second highest priority objective of the NRC-2007 report is to determine the age of the SPA basin, to anchor the basin forming epoch, so one can address both the first and second highest priority objectives with samples collected within the Schrödinger basin (e.g., [8]).

The Schrödinger impact basin is ~320 km in diameter and has a ~150 km diameter mountainous peak ring rising up to 2.5 km above the basin floor. This peak ring is composed of mid- to lower crustal material uplifted

>20 km to the surface by the impact event [9]. Thus, samples of that peak ring can be used to test the lunar magma ocean hypothesis, another major concept that emerged from the Apollo program. Testing the lunar cataclysm and lunar magma ocean hypotheses are but two of the exciting scientific issues that can be addressed within the Schrödinger basin.

On the exploration side, Schrödinger also hosts an immense pyroclastic vent that spewed, in a volatile-rich cloud, magmatic debris across a portion of the basin floor. This vent may be the largest indigenous source of volatiles in the south polar region of the Moon [10]. In anticipation of the in-situ resource (ISRU) potential of that vent, it was one of the primary exploration targets during the Exploration Systems Mission Directorate (ESMD) phase of the Lunar Reconnaissance Orbiter mission.

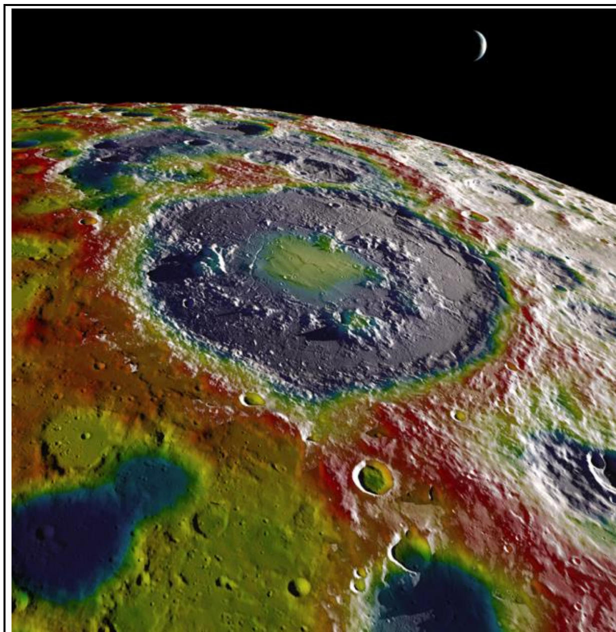

Figure 6. Orbital perspective of the ~320 km diameter Schrödinger basin on the lunar farside, looking from the north towards the south pole, with the Earth visible beyond the pole. GRAIL free-air gravity [15] mapped over LOLA- and LRO-derived terrain. NASA's Scientific Visualization Studio.

Because the Schrödinger basin is such an attractive scientific and exploration target, it has been used for several mission concept studies to drive operational trade studies and define mission requirements for geologic studies. For example, a human-assisted lunar sample mission lasting a single sunlit period was devised for a robotic rover teleoperated by crew on the Orion vehicle [11]. Because the Schrödinger basin is such a large and diverse target, potentially several completely unique missions can be flown to the basin. Thus, a robotic sample return mission over a period of 3 years, involving crew in an exploration deep space habitat, has also been explored [12].

The development of teleoperation of rovers can then be used to drive small pressurized rovers between landing sites for crew when they return to the surface in a series of five proposed missions [13, 14]. Thus, teleoperations are an essential component of both the robotic precursor missions and the subsequent human missions to the lunar surface.

4.3 Low Radio Frequency Observations of the Universe's Cosmic Dawn

After the geological samples have been launched for rendezvous with Orion, the rover can then deploy a low frequency radio telescope [16]. Radio observations below 100 MHz uniquely probe the earliest generations of stars in the Universe (Cosmic Dawn). The lunar farside affords a matchless platform for such observations, because this frequency range is contaminated on Earth by human-made signals (e.g., FM radio, digital TV) and is highly distorted by the Earth's ionosphere [17]. Neutral hydrogen fills the intergalactic medium surrounding the first stellar populations, and it is modified by heating and ionization as these first luminous objects begin to radiate. A hyperfine transition of neutral hydrogen emits photons (at rest wavelength 21-cm and frequency 1.42 GHz) with redshifted frequencies 20-100 MHz which allows us to indirectly examine the birth and evolution of primordial stars for the first time.

Two measurement approaches exist to survey the hydrogen around the first stars. First, the sky-averaged spectrum is the most basic quantity that can be measured with either a single antenna [18] or a compact array of dipole antennas [19]. Second, the power spectrum of hydrogen fluctuations allows the growth of structure (the "cosmic web") in the early Universe to be tracked. These observations require a more extensive array of 100's to 1000's of dipole antennas distributed over an area with a diameter of >10 km. It is potentially more powerful than the sky-averaged spectrum, but it is also more difficult to measure because the signal from each structure is very small. Either measurement requires significant sensitivity within the radio-quiet environs of the lunar farside.

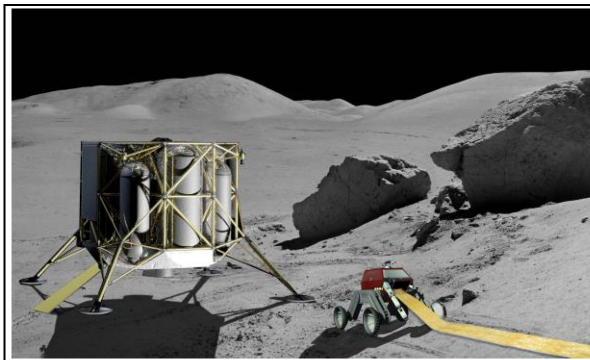

Figure 7. Surface teleoperation of rovers from orbiting facilities is a key technology for astronaut-assisted deployment of a lunar farside polyimide antenna and collection of geological samples. Image is courtesy of Robert MacDowell and NASA GSFC.

One viable approach to distribute an array of dipoles on the lunar surface begins with the deposition of electrically conducting antennas on a polyimide substrate [20]. The polyimide film with embedded antennas can then be rolled-out on the lunar surface with a teleoperated rover (Figure 7). This approach has significant benefits, most notably small volumes for transport and multiple deployment approaches. The gain/beam of the antenna will be dependent upon the sub-surface properties at the deployment site so this area will require further characterization. After deployment, the antennas can then be electrically phased for power spectrum measurements or incoherently combined for sky-averaged measurements. This later approach may be most appropriate for a pathfinder array requiring a smaller number of antennas but will be challenging due to the control of systematics. These trades are currently under study by our NASA Solar System Exploration Research Virtual Institute NESS (Network for Exploration & Space Science) team.

5. CONCLUSIONS

Surface Telerobotics has the demonstrated potential to conduct cutting-edge research in lunar geology and cosmology from the lunar farside using NASA's Orion and Deep Space Gateway infrastructure. In addition to the early science that will be accomplished during extended stays in cis-lunar space, key technologies and operational strategies will be matured that will feed-forward to the first human missions to Mars. These first astronaut operations at Mars will likely be orbiting missions where teleoperation of multiple, low-latency, high velocity, robotic rovers [21] could result in exploration traverses of 10's or even 100's of kilometers over Martian terrain before humans reach the surface. The Deep Space Gateway will open the door to scientific investigations of the Moon and Mars.

ACKNOWLEDGEMENTS

This work was partially supported by Cooperative Agreements from the NASA SSERVI institute to JOB and DAK. The U. Colorado student telerobotics project was funded in part by the Lockheed Martin Space Systems Company. We thank Bob MacDowall, Joseph Lazio, Dayton Jones, Raul Monsalve, Benjamin Mellinkoff, Matthew Spydell, and Wendy Bailey for their contributions to components of the projects discussed herein.

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