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Space Science Opportunities Augmented by **Exploration Telepresence**

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Space Science Opportunities Augmented by Exploration Telepresence

Study Report prepared for the W. M. Keck Institute for Space Studies (KISS)

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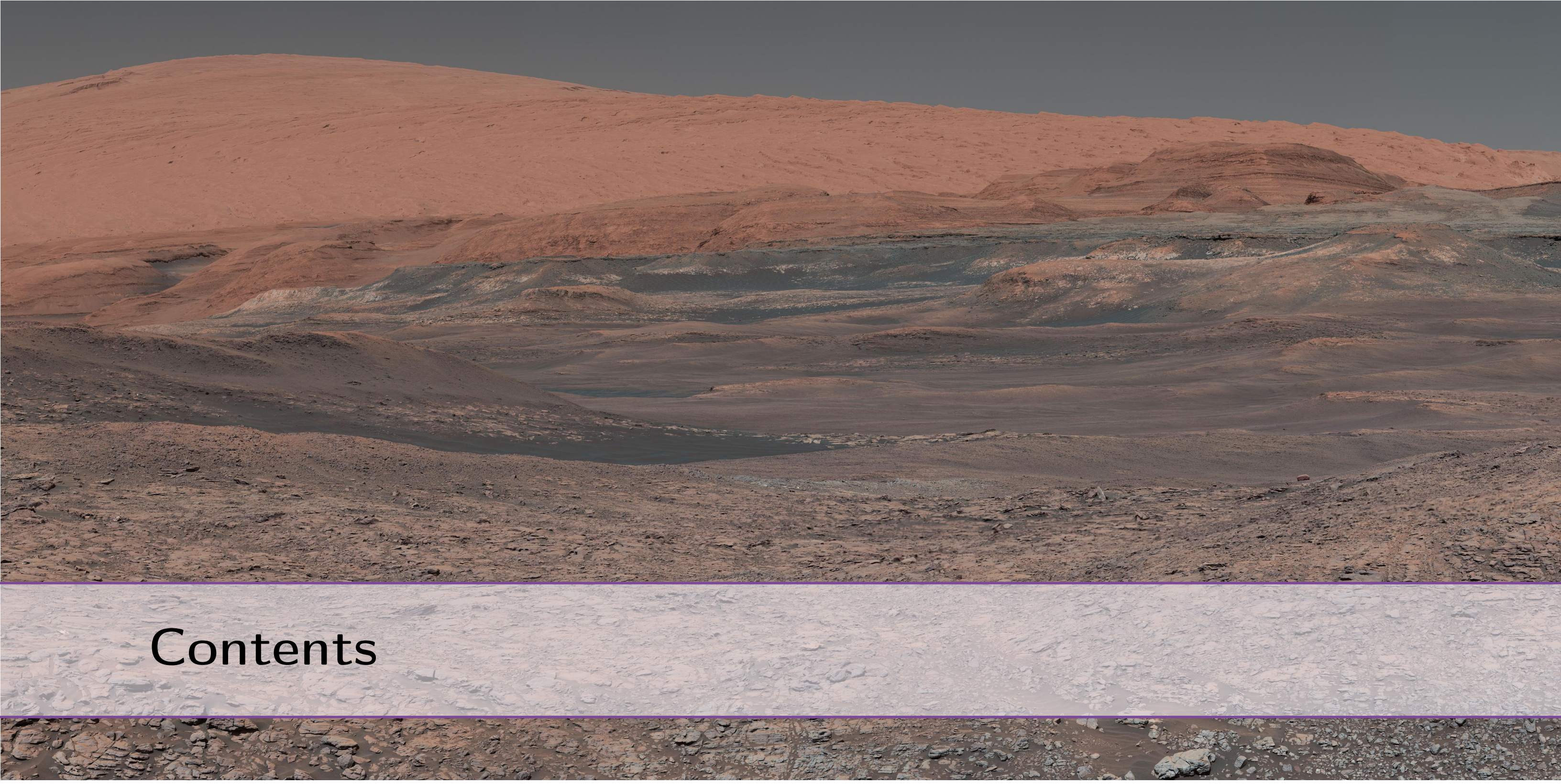

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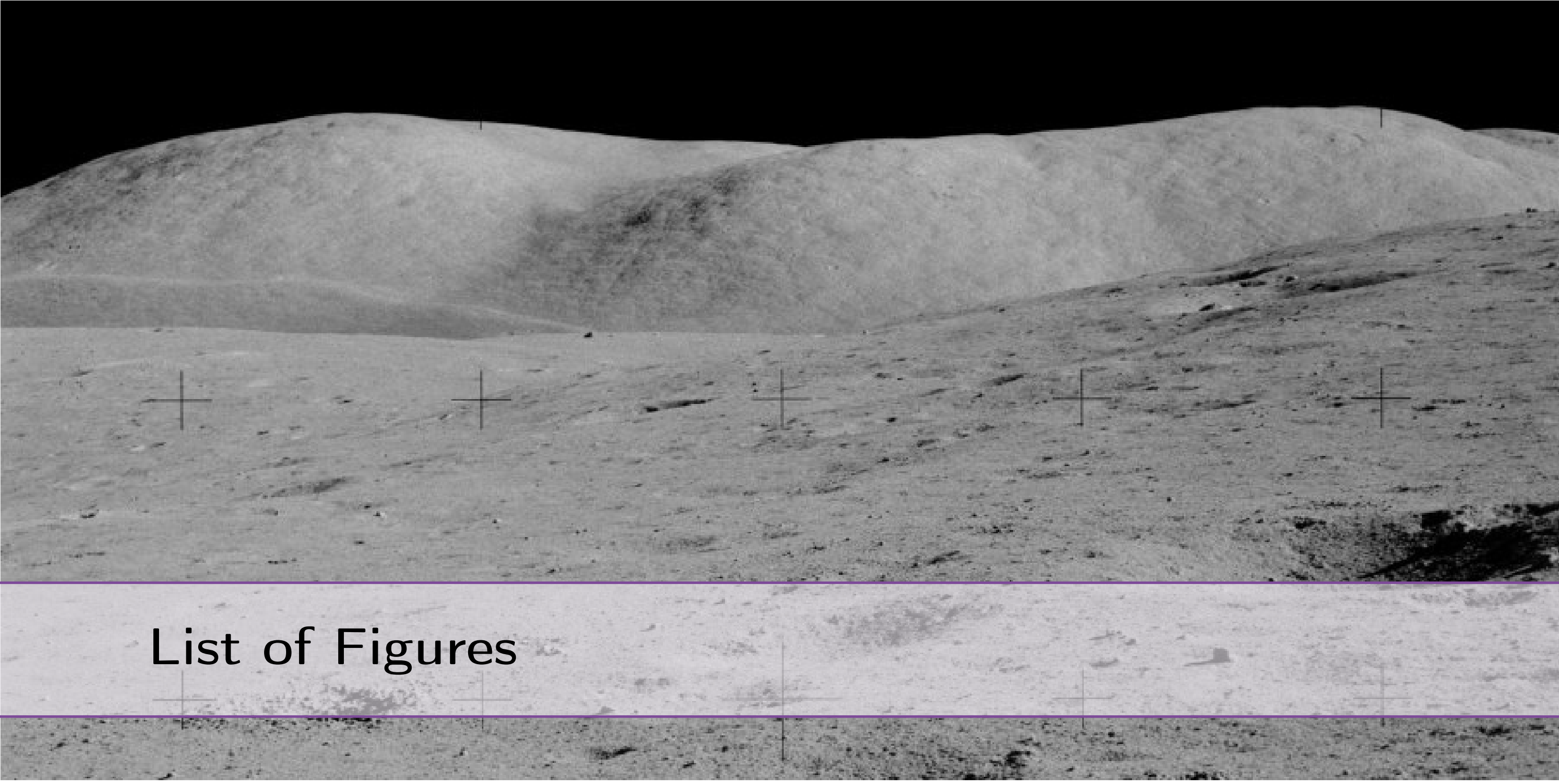

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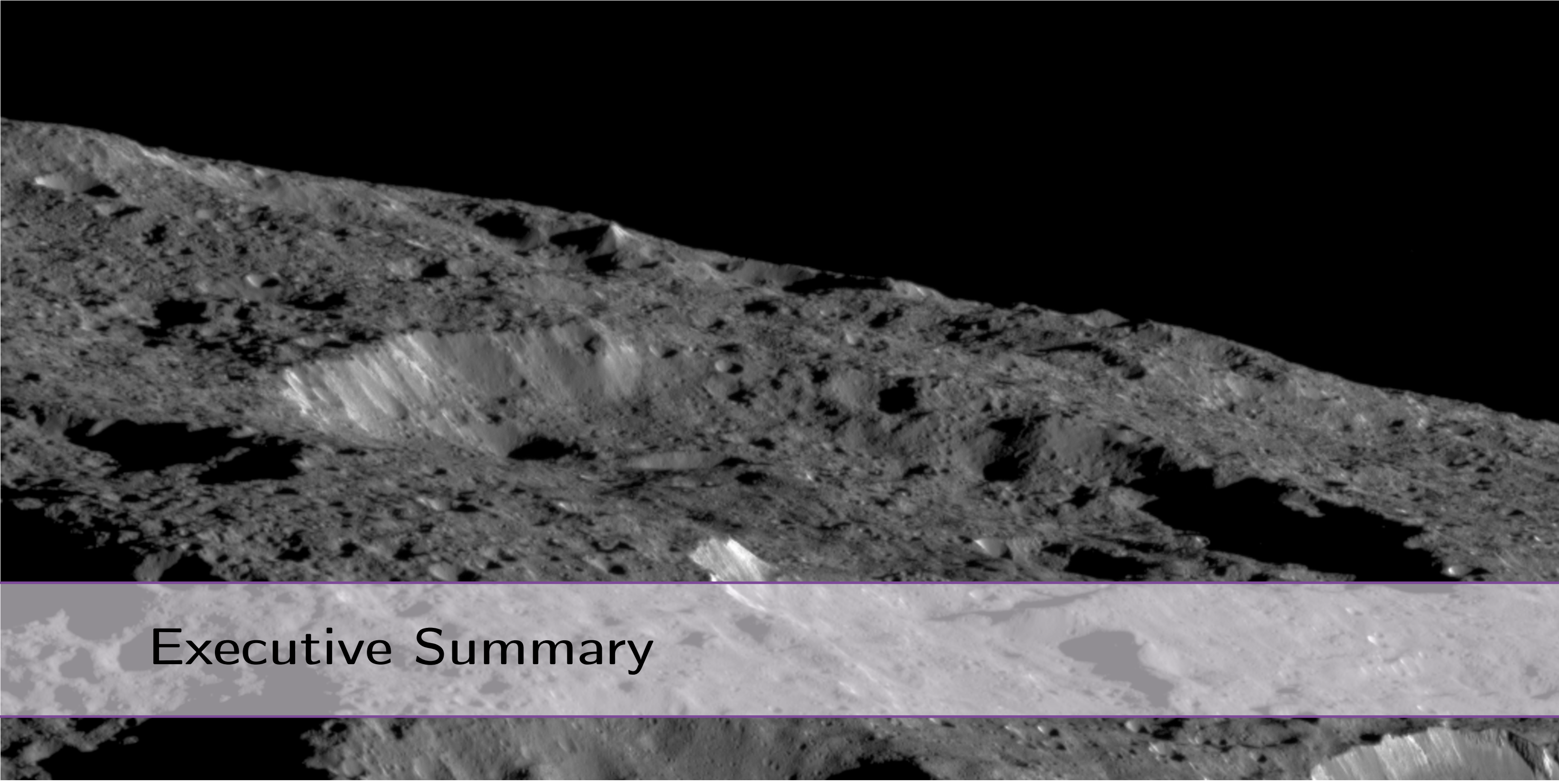
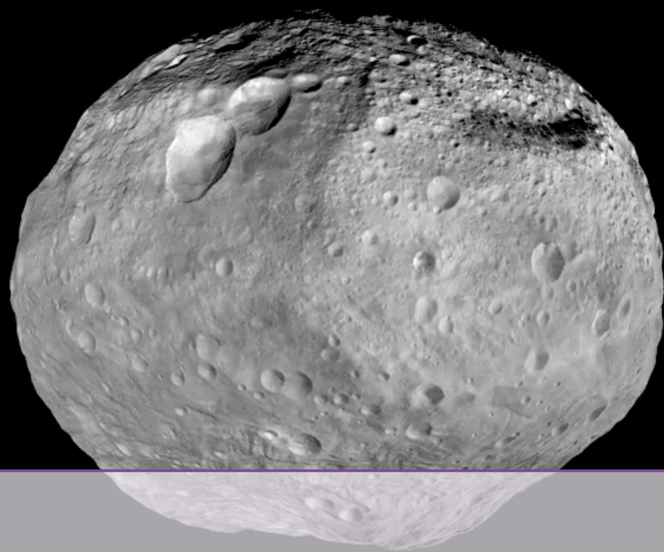


Executive Summary

In 2016 and 2017, the Keck Institute for Space Studies hosted two workshops titled "Space Science Opportunities Augmented by Exploration Telepresence." World-class representatives from telerobotics, planetary science, and human spaceflight gathered together to evaluate the benefits and challenges of pursuing a strategy for collaborative human and robotic planetary exploration. By exploiting the rapid progress in robotic telepresence technology, humans in habitats proximal to an exploration destination will, through robotic surrogates, achieve immersive presence at multiple exploration sites, including those considered too dangerous for astronauts. Employing this strategy will greatly accelerate and increase scientific return while substantially lowering costs and risks.

These workshops revealed there has been limited study of the advantages of conducting planetary science via low-latency telepresence (LLT). This report recommends that space agencies such as NASA substantially increase planetary science return with greater investments in LLT research, field tests, and deployment when actually sending humans to off-Earth exploration sites.



1. Introduction

Since the end of the Apollo missions to the lunar surface in December 1972, humanity has exclusively conducted scientific studies on distant planetary surfaces using teleprogrammed robots. Operations and science return for all of these missions are constrained by two issues related to the great distances between terrestrial scientists and their exploration targets: high communication latencies and limited data bandwidth.

Despite the proven successes of in-situ science being conducted using teleprogrammed robotic assets such as Spirit, Opportunity, and Curiosity rovers on the surface of Mars, future planetary field research may substantially overcome latency and bandwidth constraints by employing a variety of alternative strategies that could involve: 1) placing scientists/astronauts directly on planetary surfaces, as was done in the Apollo era; 2) developing fully autonomous robotic systems capable of conducting in-situ field science research; or 3) teleoperation of robotic assets by humans sufficiently proximal to the exploration targets to drastically reduce latencies and significantly increase bandwidth, thereby achieving effective human telepresence.

This third strategy has been the focus of experts in telerobotics, telepresence, planetary science, and human spaceflight during two workshops held from October 3–7, 2016, and July 7–13, 2017, at the Keck Institute for Space Studies (KISS). Based on findings from these workshops, this document describes the conceptual and practical foundations of low-latency telepresence (LLT), opportunities for using derivative approaches for scientific exploration of planetary surfaces, and circumstances under which employing telepresence would be especially productive for planetary science.

An important finding of these workshops is the conclusion that there has been limited study of the advantages of planetary science via LLT. A major recommendation from these workshops is that space agencies such as NASA should substantially increase science return with greater investments in this promising strategy for human conduct at distant exploration sites.

2. Science Rationale for Exploration Telepresence

The establishment of interplanetary scientific operations using robots is a paradigm on which much of current planetary science is based. While it enables Earth-based scientists to make measurements they themselves cannot collect, the speed of light and the large distances nevertheless severely inhibit interaction and productivity. Long time delays (i.e., high latencies) are unavoidable.

NASA's primary approach to eliminate latency has been to physically put humans at each site with their "boots on the ground" (Figure 2.1). Although widely accepted, this approach is very expensive to achieve and entails substantial hazards to astronauts. A safer and less expensive approach is to apply remote robotic technologies when human scientists are nearby. Whether astronauts are in spacecraft orbiting overhead (Figure 2.2), or in a nearby surface habitat, they can have real time operational control of telerobots on the surface of any planetary body, at many different sites, giving them global vision, mobility, and dexterity to conduct field operations. This capability allows astronauts to interact with the environment without being physically present at each site; thereby increasing the amount and quality of the science that can be collected by each crew member. We refer to this new approach as exploration using LLT.

2.1 Exploration Telepresence

This LLT concept for exploration employs near real time (low-latency) telerobotics to provide high-fidelity remote human presence. This telepresence includes the traits of stereoscopic vision, agile mobility, force-sensing dexterity, and other sensory modalities. Humans who teleoperate the robotic surrogates need to be in relatively close proximity to these robots to

Figure 2.1: Apollo 17 astronaut Harrison Schmitt collects samples from Taurus-Littrow (Image: NASA).

allow for low-latency high-bandwidth sensing and control. Unlike conventional teleprogrammed robotic control from the Earth that is significantly delayed by speed-of-light communications and relay network latencies, LLT enables astronaut presence manifested in real time. This strategy's benefits increase as the destination's distance from Earth increases.

The idea of using LLT for exploration telepresence is not entirely new. Others have suggested this approach over many decades (see Appendix B).

In an optimally engineered system, LLT allows a human teleoperator to feel as if he or she is actually present in situ at the site (Figure 2.3). As sensory fidelity increases and the temporal disparity decreases, the distinction between actual physical presence and telepresence diminishes. This new approach, where humans need not be routinely exploring out on the surface of the planet, avoids putting them at risk in mobility-limited extra-vehicular activity (EVA) garb while exposed to radiation and other environmental hazards.

Because LLT does not require humans to be physically at the exploration site, it is potentially advantageous in terms of schedule, cost, and risk. Humans in orbit can extend their presence electronically to multiple sites on a planetary surface, and that presence can be sterile, alleviating planetary protection concerns. Such activity removes limitations and risk associated with human EVA. Ongoing innovation in telerobotic and communication technologies may thus have enormous impact on future space missions. For example, exploration telepresence can be used to send human presence where "boots on the ground" are not an option (e.g., the surface of Venus, under the methane lakes of Titan, etc.). It embraces both robotics

Figure 2.2: Concept of a scientist in an orbital habitat conducting exploration telepresently (Image: Lockheed Martin).

and human spaceflight, representing a synergistic partnership of those capabilities to pave the way for eventually putting humans physically on planetary surfaces. It is important to understand that concept development to do science with LLT has been highly limited thus far—e.g., driving rovers around and deploying sensor stations. Driving around is relatively easy but is extremely inefficient and time consuming. However, exploring opportunities for LLT operations that result in important scientific outcomes will require a higher degree of situation awareness and adaptive capabilities than have been explored through previous tests or demonstrated through high-latency activities such as exploring Mars with the Curiosity rover.

Figure 2.3: (Left) Scientist in an orbital habitat conducting LLT; (center) LLT allows a human teleoperator to feel as if he or she is actually present in situ at the site; (right) In situ rover responding to real time commands from an astronaut (Image: Lockheed Martin)

We recognize that LLT departs from the established planetary exploration mission concepts of either distant-landed teleprogrammed robots, such as the Mars Exploration Rovers (Spirit and Opportunity), and the Mars Science Laboratory (Curiosity), controlled by humans on Earth (high-latency telerobotics, or HLT). Likewise, LLT is distinct from the "historical" image of human exploration solely conducted with "boots on the ground." While the LLT strategy presented in this report depends critically on human spaceflight, it combines both landing telepresence robots and locating the human teleoperators within a relatively short distance of these robots. Through these telepresence robots, the humans' capabilities can be augmented while increasing their efficiency and reducing risk to the astronauts. For all pragmatic intents and purposes, those humans are really "present" where the telepresence robots are landed and use them as sensory, manipulation, and mobility surrogates. It may also be possible that a suitably designed system (user interface, communication system, robots, etc.) will enable a human to remotely have "super-human" capabilities (in terms of precision, production, endurance, sensing, etc.) and for a single human to be present in more than just one location/body at a time (i.e., not just one-to-one control, but perhaps one-to-many operations; see Section 3.1). This strategy can be considered a true implementation of human–robot real time collaboration.

2.2 Keck Institute for Space Studies Workshop on Exploration Telepresence

Current planning at NASA and recent independent studies have noted the potential benefits of LLT (see Appendix A and Lester et al., 2017). To be comprehensive and to formally address the benefits and drawbacks of LLT, a multidisciplinary review was organized by the Keck Institute for Space Studies (KISS): "Space Science Opportunities Augmented by Exploration Telepresence." The Institute provided the forum for identifying the necessary steps that need to be taken for collaborative human and robotic exploration. This includes the development of software and hardware, risk reduction, and field training of astronauts and robots.

World-class representatives from telerobotics, planetary science, and human spaceflight (Figure 2.4) gathered at KISS to evaluate the benefits and challenges of exploration telepresence; two workshops were held, one October 3–7, 2016, with a continuation over July 7–13, 2017. Workshop details are available here:
Workshop 1: `http://kiss.caltech.edu/workshops/telepresence/telepresence.html`
Workshop 2: `http://kiss.caltech.edu/workshops/telepresence/telepresence2.html`

The workshops produced a critical review of the LLT strategy, namely, to position humans in habitats proximal to an exploration destination from which they would, through robotic surrogates, achieve high quality human presence there. Because this strategy does not require humans to be physically at the destination, it will potentially lower both cost and risk. At Mars, for example, humans based in orbit or on a moon would conduct LLT surface exploration while avoiding the considerable expense and risk of Mars entry, descent, and

Figure 2.4: Representatives from telerobotics, planetary science, and human spaceflight gathered at the Keck Institute of Space Sciences to evaluate the benefits and challenges of exploration telepresence (Image: KISS).

landing—techniques have yet to be invented, let alone proven, for human exploration. LLT would avoid the additional risks of surface environmental and physical hazards and the ascent to orbit. LLT would also avoid the attendant costs of delivering system mass and propellant to the surface. For example, a piloted Mars ascent vehicle (MAV) embodies an architectural mass component that cannot be subdivided and thus dictates a minimal landed mass capability for Mars entry–descent–landing (EDL). Even if in-situ resource utilization (ISRU) capabilities are developed such that a MAV can be landed with a partial propellant load, that landed mass will exceed 20 tons (Drake, 2009). Current Mars EDL technology is limited to landed masses no more than about 1 ton.

From their habitats, humans can explore multiple surface sites, including those determined to be too dangerous for human visits. LLT via sterile, robotic surrogates should aid planetary protection goals, too. This refined paradigm represents a synergistic partnership between humans and robots that supports both effective exploration before astronaut arrival, and more wide-ranging exploration when humans do physically reach an exploration destination.

The rapid advance of telepresence capability—situational awareness, dexterity, and mobility—is beginning to impact the way we plan solar system exploration. For planetary destinations, the distances are so large that communication latency from Earth is far higher than the human reaction time. However, if LLT from a proximal vantage point can be established, this barrier to high quality exploration can be overcome.

Significant topics addressed at the KISS workshops included identifying scientific exploration tasks that LLT might augment (see Section 5.2) and challenges that must be overcome for the vision of LLT field science to become a reality (see Section 6.2). Applications to planetary geology and astrobiology were formally examined, and the enabling cases for other sciences were also considered. Overall, participants were interested in exploiting the rapid progress in robotic telepresence technology to increase science productivity at distant destinations.

The workshop was devoted to establishing the credibility of, and the challenges to, doing fundamental planetary science with LLT. For example, one primary area of planetary science is field geology (see Section 5.2.1). Terrestrial field geology is currently done almost entirely by humans in situ (simply because humans are cheaper than telepresence robots). While there is no significant working knowledge for field geology conducted telepresently, we do have some working knowledge of undersea science conducted using telerobotics (see Section 3.2). Such knowledge, along with other current telepresence application examples, helped to inform this strategy for off-Earth LLT.

Many commercial and defense tasks, such as undersea cable and pipeline maintenance, agricultural vehicle driving, surgery, mining, robotic aerial vehicles, search and rescue units, as well as office and personal robotics, each employ some of the telepresence capabilities that will be required to conduct science in this way (see Section 3). While LLT operational concepts and technology development were identified, we did not focus on a specific mission concept or technology roadmap. These are subjects appropriate for follow-on efforts.

2.3 Strategic Relevance of LLT

Human exploration in the space environment is inherently difficult, costly, and dangerous. Planetary environments also introduce the possibility of contamination in both directions (to and from humans). The most general strategic value of LLT is the ability to place human cognition and rapid human response times in an environment without having to place a human physically in that environment. Certain environments may be problematic to human physical presence for a variety of reasons, including a) safety (e.g., radiation, temperature, illumination, etc.); b) difficulty of access (including landing in the gravity well of a planetary surface); c) planetary protection concerns, such as "Special Regions" exploration (regions where life may be extant); and (d) logistics (humans need to breathe, eat, etc., so a human surface mission requires us not only to get humans to the surface, but also to provide the supplies necessary to keep them alive). The primary advantage of having humans directly in an LLT operations loop is their ability to exercise judgment and react quickly across a broad range of activities, from system maintenance to science operations (Figure 2.5). Supervised autonomy and fully autonomous systems have the potential to accomplish complex tasks rapidly, and such systems are being applied to nearly all areas of space activities. However, we may reasonably expect that many exploration scenarios will not be safe, optimal, or feasible using fully autonomous systems alone. In particular, many possible contingency scenarios may demand rapid and flexible human judgment and physical action (Podnar et al., 2007). Providing that "human touch" will undeniably advance the entire spectrum of science activities. In some cases, LLT may actually be more effective than physical presence in environments where dexterous reach and visibility might be inhibited by spacesuits, obstacles, etc.

Figure 2.5: Concept for exploration telepresence on Mars from a habitat in orbit. Astronaut scientists safely in orbit over Mars control telerobotic surrogates on the surface. These surrogates give the scientists real time vision, dexterity, and mobility. They can operate a diverse suite of surface tools at many different locations on the surface, providing real time electronically mediated presence (Image: NASA Goddard Space Flight Center).

For at least the next generation, Mars is a primary goal for human exploration. In preparing for an eventual landing and sustainable human presence on Mars, LLT offers the opportunity to efficiently and reliably conduct many tasks that should be performed prior to crew arrival. Even without the requirement for pre-landing work, any Mars orbital precursor (for example, a crewed mission to either Deimos or Phobos; Singer, 1984), could take advantage of that human presence near Mars to conduct activities on the surface—including quality science (Adamo et al., 2014; Burley et al., 2001; Drake, 2009; Folta et al., 2011; Taff, 1985). These activities could not only help reduce the crew's post-landing workload but also help inform outpost and surface science planning.

While an eventual goal of human exploration is to land on Mars and sustain a permanent presence there, a crewed landing may not be possible for some time (Berger, 2017). Under those circumstances, exploration telepresence could be used to slowly and "opportunistically" prepare for the eventual crewed landing, in part by performing extended, in-depth science. Such a science campaign might also make it easier to meet contamination control and planetary protection requirements (Adamo and Logan, 2016).

Even after humans occupy habitats on the surface of Mars and other off-Earth exploration destinations, they will undoubtedly use LLT for a majority of activities outside those habitats, possibly on a global scale. The same productivity, safety, health, and cost savings benefits realized through LLT from proximal or orbiting habitats apply to LLT from habitats physically present at a destination.

Finally, there are transient phenomena that would benefit from a rapid scientific response (e.g., dust and mass movement, certain kinds of geochemistry, boundary layer dynamics, possible subsurface liquid environments, and biological dynamics). The operation of aerial vehicles, drilling apparatuses, or subsurface vehicles in liquid environments, could benefit greatly from the rapid human response times facilitated by LLT.

2.4 Mission Cost Reductions

This subsection details a formal approach to evaluating the cost of crewed missions to the Moon and Mars, comparing both landed and orbiting missions using LLT. The examples include three different propulsion technologies and focus on the cost of transporting the mass necessary to the destination. A reasonably objective cost metric, free from programmatic or currency inflation influences, is initial mass in low-Earth orbit (LEO). This metric assumes all material required to transport humans off-Earth must first be launched to LEO, but assuming another "departure gateway" transport node in the Earth–Moon system, would serve as a similar cost metric among exploration destinations of interest. In this application, the "rocket equation" (Taff, 1985) computes the ratio of mass in LEO divided by mass transported to the destination $m_{\text{LEO}}/m_{\text{D}}$. This computation utilizes the specified change-in-velocity magnitude Δv required for transport, together with transport propulsive efficiency termed "specific impulse" or I_{SP} and Earth surface gravity acceleration $g = 9.80665$ m/s^2, as in Equation 2.1:

$$m_{\text{LEO}}/m_{\text{D}} = e^{\Delta v/gI_{\text{SP}}} \tag{2.1}$$

Figure 2.6 plots the $m_{\text{LEO}}/m_{\text{D}}$ ratio as a function of Δv for several I_{SP} values. Note that in Figure 2.6, Δv values between LEO and specific annotated destinations (dashed vertical lines) are one-way for the sake of simplicity. Associated $m_{\text{LEO}}/m_{\text{D}}$ ratios would approximate round-trip human architectures whose return consumable mass is pre-positioned near the destination. Architectures departing LEO with all consumable masses required for a round trip will have a considerably greater $m_{\text{LEO}}/m_{\text{D}}$ ratio to a particular destination than that appearing in Figure 2.6 because the associated Δv is effectively doubled for those architectures.

When assessing the consequences of Figure 2.6, it should be noted that off-Earth human transport requires orders of magnitude more mass at the destination than does exclusively robotic exploration. Adding consumables pre-emplaced near the destination in support of

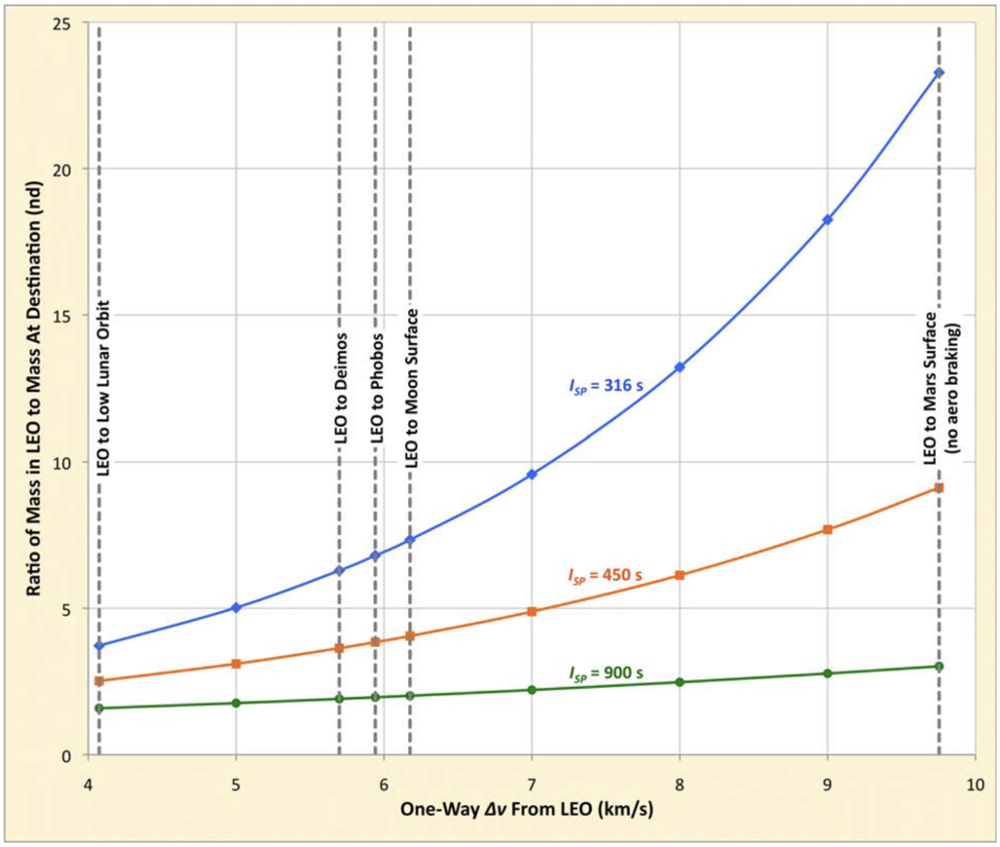
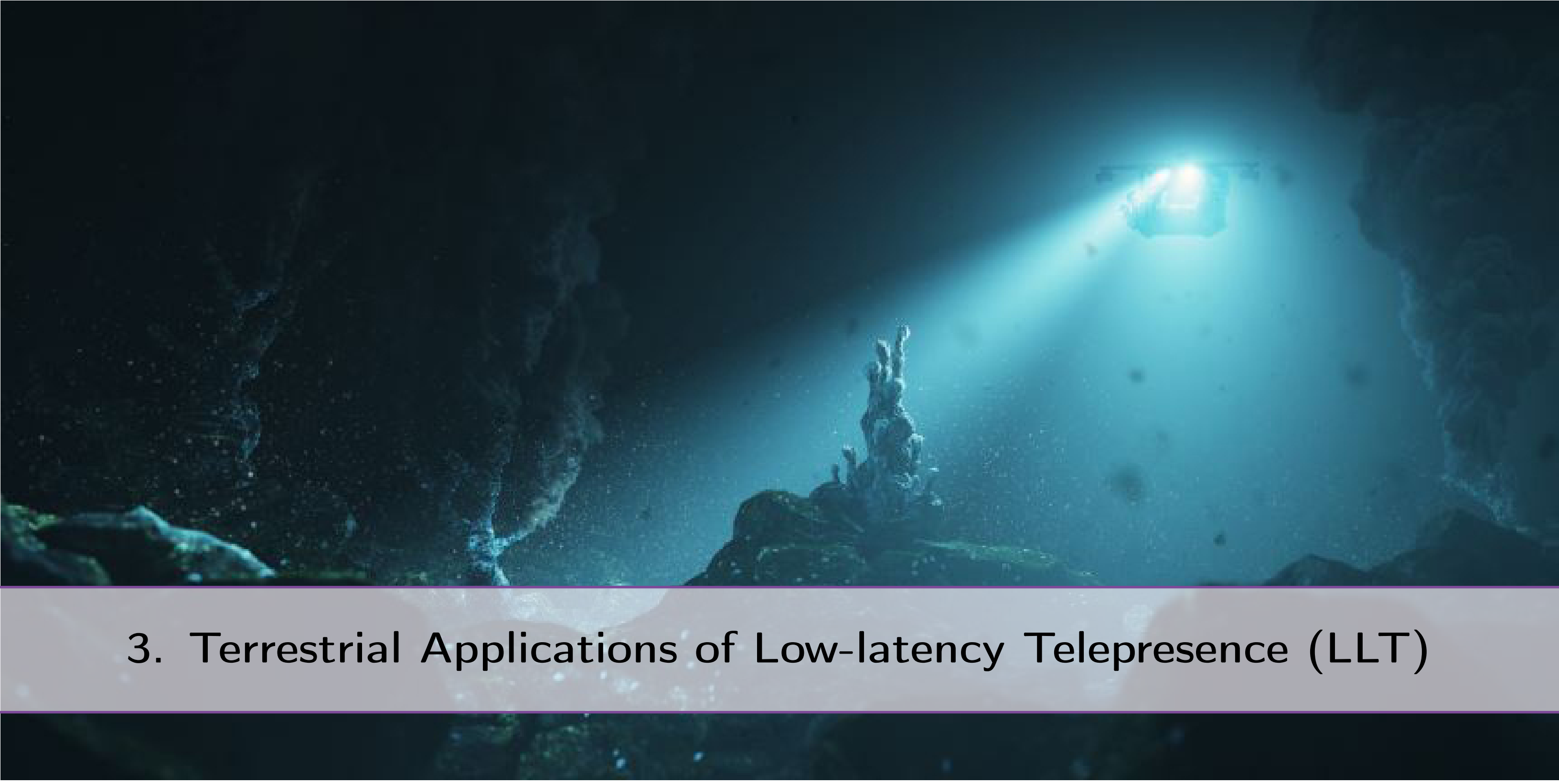


Figure 2.6: The ratio of enabling mass in LEO to mass thereby delivered to an off-Earth destination is plotted as a function of Δv associated with this mass transport. Because the mass ratio is also a function of transport propulsive efficiency I_{SP}, three color-coded plots are provided. The blue $I_{SP} = 316$ s plot corresponds to chemical propulsion systems consuming hypergolic liquids storable at room temperature (such as hydrazine and nitrogen tetroxide). The orange $I_{SP} = 450$ s plot corresponds to chemical propulsion systems consuming cryogenic liquids (such as liquid hydrogen and liquid oxygen). The green $I_{SP} = 900$ s plot corresponds to nuclear thermal propulsion systems consuming low-mass molecules (such as H_2).

returning humans to Earth, total mass required at a destination such as the Moon or Mars can easily fall into or exceed the 40,000 kg to 400,000 kg range (the latter being close to International Space Station mass; Adamo and Logan, 2016; Drake, 2009).

As a Figure 2.6 assessment example, consider the orange $I_{SP} = 450$ s plot and compare the LEO mass ratio for one-way transport to the outer Martian moon Deimos (3.637) with that for one-way transport to the surface of Mars (9.118). Even though the two destinations are proximal to each other, the cost metric for transport to the Martian surface is 2.5 times greater than for transport to Deimos. Thus, it can be asserted that two human missions in Mars orbit can be conducted for a cost comparable to a single human mission to the Martian surface. Even at the current state of the art in robotics and astronautics, it is a dubious claim that the single surface mission, with or without LLT, could explore as much of Mars as could two orbiting missions with LLT facilitated by robotic surrogates on the surface. This example illustrates how placing humans at interplanetary destinations only 20,000 km apart can entail dramatically differing costs.



3. Terrestrial Applications of Low-latency Telepresence (LLT)

In the contexts of data transmission and this study, latency is the round-trip light time plus communication systems delays between a human operator and a distant science target under study (reference "latency" in the glossary, Appendix C). Haptic feedback latency above 30–50 ms is well understood to be easily detectable. Studies of presence in virtual environments have shown that latencies of 50–90 ms results in reduced sense of presence (Meehan et al., 2003). As identified in the following subsections, acceptable performance can be achieved with latencies between 200–500 ms.

Four specialized professional fields have been on the forefront of expanding the use of low-latency telepresence (LLT): surgical medicine, ocean exploration, mineral mining, and the military. These subsections include brief examples of each.

3.1 Surgical Medicine LLT

For the last two decades, telepresence has become commonplace in the practice of medicine. Many medical providers offer remote audio-visual consultation between a doctor and a patient through a smartphone, tablet, or computer. Certain robot systems allow physicians more thoroughly to examine (teleconference robots), diagnose (robot-assisted teleradiology), or even operate on a patient at a different geographic location (Hoeckelmann et al., 2015).

Minimally invasive robotic systems (e.g., the da Vinci Surgical System by Intuitive Surgical; Figure 3.1) enable remote surgical procedures. While current practice locates the surgeon in close proximity to the patient, Intuitive Surgical is exploring telesurgery as a way to perform operations over long geographical distances, eliminating the need for physically co-locating the physician and patient. This can also support surgeon-to-surgeon proctoring and coaching.

However, surgical telerobotics, when implemented intercontinentally, can suffer from significant latencies. Such surgeries require a high degree of precision dexterity and human awareness, and are intolerant of both mistakes and long task completion time. The impact of latencies (of up to about 500 ms) has been established with some care for surgical telerobotics (e.g., Anvari et al., 2004; Perez et al., 2016). Based on both task completion time and error rate, acceptable surgical performance requires latencies less than 500 ms. More detail on this research and technology development is included in Section 6.2.

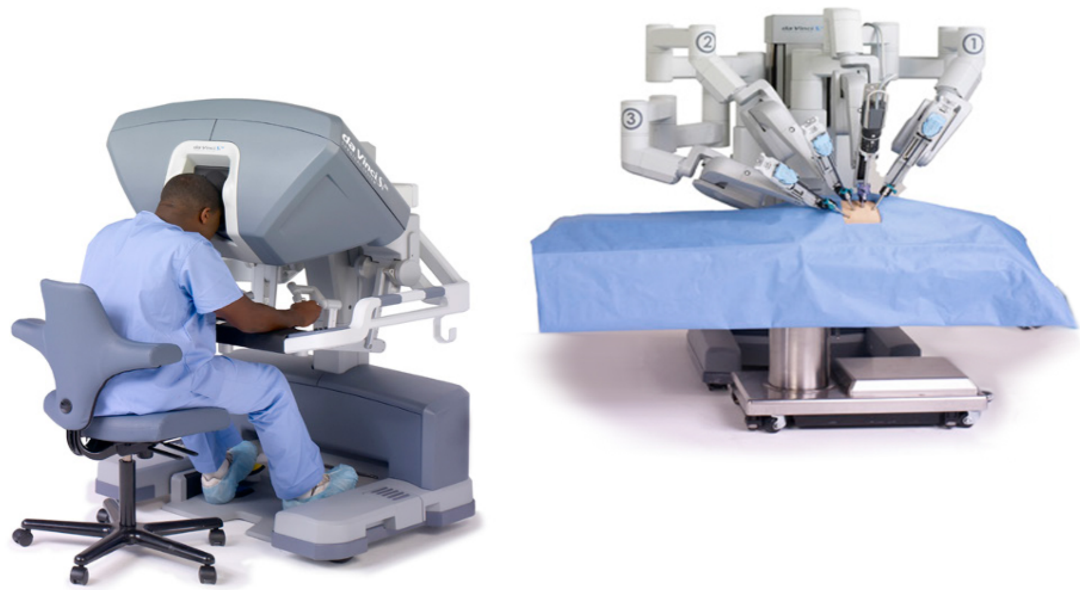


Figure 3.1: The da Vinci Surgical System enables remote surgical procedures using LLT. (Image: Intuitive Surgical).

3.2 Ocean Exploration LLT

Exploration in the deep ocean shares many of the same limitations that distant planetary exploration has: humans must wear special suits to withstand the environment, carry limited consumables that restrict exploration time, and contend with communication issues. Submarine exploration is therefore an excellent example of the technologies that will serve LLT planetary exploration.

3.2.1 Deep Sea Exploration using LLT

Deep ocean exploration has long employed remotely operated vehicles (ROVs) for a variety of tasks. Current ROVs are robots controlled by scientists through a long cable that connects the robot to the ship. One example is OceanOne, built at Stanford University (Figure 3.2). OceanOne was tested at the wreck site of La Lune, a French warship that sank in the Mediterranean in 1664 off of Toulon. OceanOne includes a force-reflecting arm, high-definition video cameras, and many other sensors. Pilots aboard a support ship operate

OceanOne via a long, ship-to-robot high-bandwidth and very low-latency fiber-optic cable transmitting operator commands, video, and sensor data. Through the use of haptic joysticks, the operator can feel the lightness or heaviness of a grasped object, thus giving researchers a much more hands-on feel.

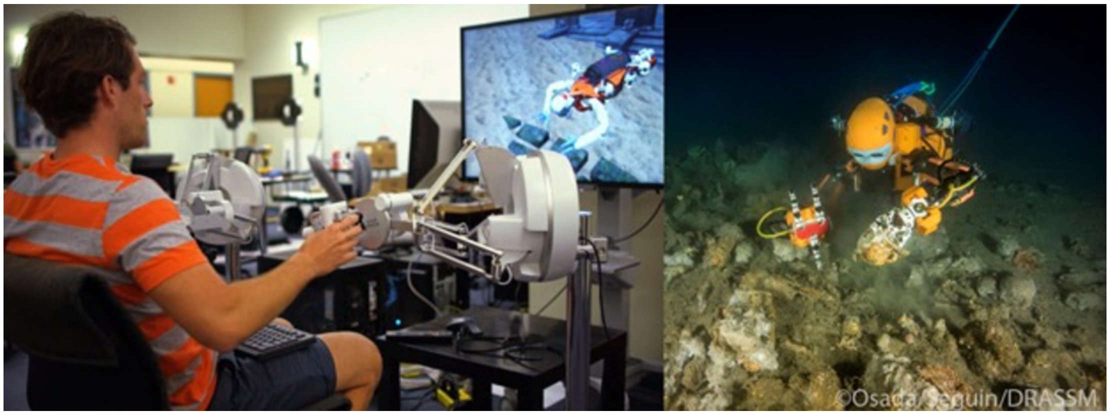


Figure 3.2: (Left) Teleoperator controlling the Stanford University's humanoid robotic diver, OceanOne, employs force feedback manipulators. (Right) OceanOne examining and collecting samples (https://www.spe.org/en/jpt/jpt-article-detail/?art=767).

3.2.2 Deep Sea Maintenance using LLT

Experiments have also been conducted in controlling ROVs thousands of miles distant from the operator through satellite links and remote LLT optical communication (Doniec et al., 2010). The oil and gas industries employ LLT ROVs for construction, inspection, and maintenance of underwater equipment. One example of this maintenance has been implemented by Oceaneering. Their onshore control center in Stavanger, Norway, will be used to conduct maintenance work offshore, giving operators the ability to command underwater robots in real time (https://www.oceaneering.com).

Another company that uses and evaluates new technologies to increase the effectiveness of undersea operations with ROVs is DexROV. DexROV's goals are to reduce the latency between onshore control centers and ROVs and to develop advanced dexterous tools with the capacity to grip and manipulate underwater drilling equipment similar to a human hand (http://www.dexrov.eu).

3.2.3 Deep Sea Mining using LLT

Canadian-based company Nautilus Minerals has been preparing to begin excavating mineral deposits off the coast of Papua New Guinea. Mining a mile under the sea requires some extreme engineering designs similar to the type of engineering challenges encountered in developing space hardware. Nautilus Minerals' target is silver and copper deposits located along the seafloor with more than ten times the concentration found on similar deposits on land (Figure3.3). A 700-foot mothership controls three giant drilling machines capable of cutting, collecting, and transporting the ore while withstanding the harsh deep sea environments. All of the machines are electrically powered and connected to the surface with a long umbilical cable. Each robot has a variety of sensors, including seven cameras, nine sonar heads pointing in different directions, gyros, accelerometers, and positioning sensors (`http://www.nautilusminerals.com`).

Figure 3.3: Teleoperator in the control room on board the Nautilus Minerals Production Support Vessel controlling one of the underwater assets. At 310 tons, the bulk cutter is the largest of the three seafloor robots. Like the others, it is electrically powered and connected to the surface with a long umbilical cable (Image: Nautilus Minerals).

3.3 Mineral Mining LLT

The use of robotic, autonomous equipment is expanding in large-scale mining operations. Worldwide, mining companies have been leading the way in developing fully autonomous vehicles due in part to the operational efficiencies they offer. Companies such as Caterpillar, Komatsu, and Volvo have been developing and deploying autonomous vehicle technologies for several years; robotic mining vehicles include excavators, loaders, and trucks.

3.3.1 Semi-Autonomous Underground Load, Haul, Dump (LHD)

An "LHD" is an underground mining vehicle that loads ore from an open stope (where there is broken rock), hauls it through tunnels, and dumps it into a waiting truck to be transported to the surface. As this type of operation presents a number of hazards, such as unstable tunnel roofs in open stope areas, it is desirable to keep the operator at the surface (Figure 3.4); thus, the system is semiautonomous. Because the pile of ore in the open stope is unstructured, the human miner controls the LHD to ensure a full load is acquired, and then hands the process over to autonomous hauling and dumping actions.

Human operators are based in remotely located control stations. This provides many benefits:

- Operators are removed from the hazardous, hot, and dusty underground environment.

- A comfortable ergonomic operator station reduces operator fatigue.
- One operator can control multiple machines.
- Autonomous navigation for driving eliminates wall collision vehicle damage.
- Shift change delays and the need to evacuate during blasting are eliminated.
- Production is increased.

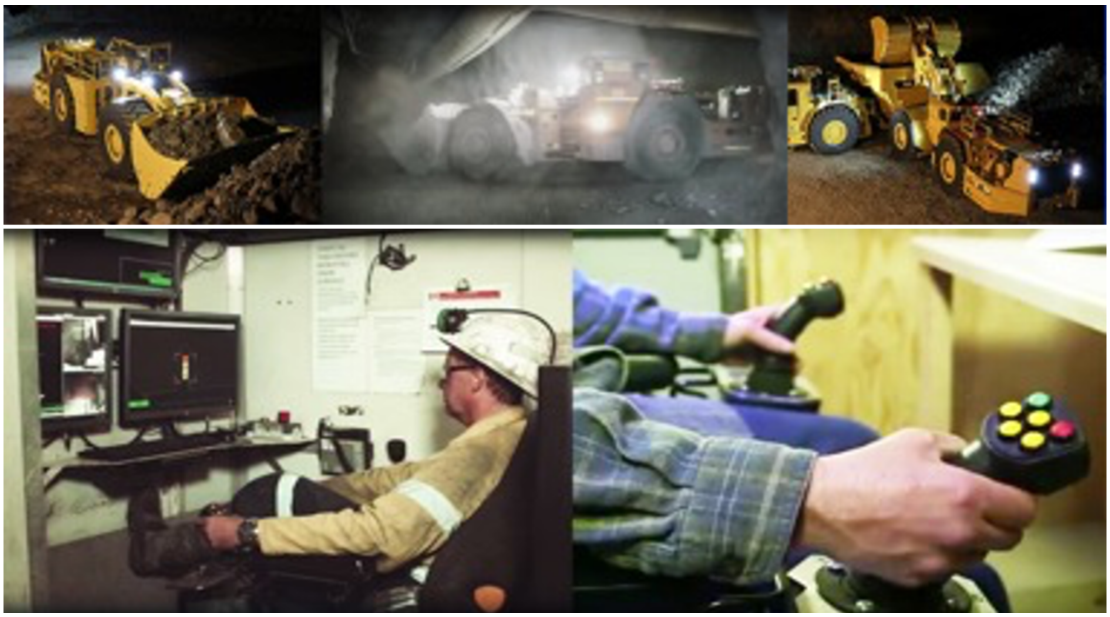


Figure 3.4: (Top) Examples of telepresent loading, autonomous navigation through tunnels, and automated dumping. (Bottom) The teleoperator monitors operation and takes control for the loading function `https://www.asirobots.com/mining/excavator` (Images: CSIRO).

This technology, developed and proven by CSIRO in Australia, is licensed to Caterpillar. The system has been sold around the world and is now in everyday use moving millions of tons of broken ore while operators sit safely in comfortable control rooms. Mines using the system have reported 40–60% productivity increases over onsite operation.

3.3.2 Telepresence Rock Breaking

Rocks that are too big to enter an ore crusher get stuck in the ore receptacle (Figure 3.5). Once stuck, it is necessary to break these into smaller pieces with a large jointed arm fitted with a hydraulic hammer. A telepresence rock breaker machine has been proven at Rio Tinto's iron ore mine in West Angeles, Australia, controlled by an operator over 1,000 km away in Perth. The telepresence view allows the remote operator to "fly around" the rock breaker machine (via mouse commands) to inspect the over-sized rocks from different angles. Once an appropriate breaking strategy is decided, the remote operator can then deploy the rock breaker arm with a live joystick. This telepresence system was also developed by CSIRO. These technologies provide higher levels of LLT immersion by delivering a wider range of more detailed, real time information to the human operator.

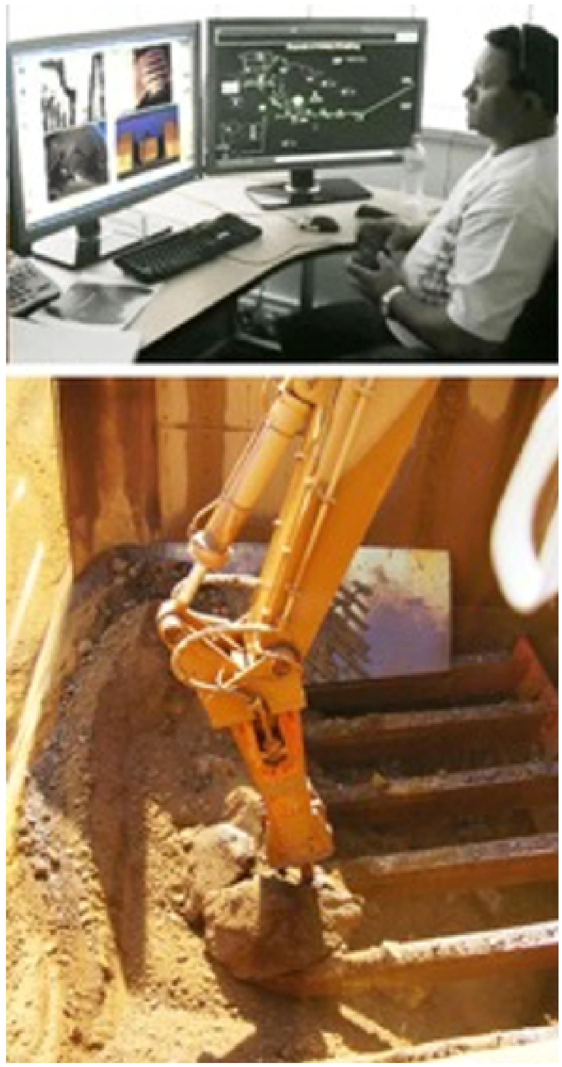


Figure 3.5: Teleoperated rock breaking (Images: CSIRO).

Production field trials in 2008 demonstrated that the telepresence rock breaker system is safe and productive—indeed sometimes faster than traditional on-site operation. The systems allow one operator to remotely monitor and take direct telepresent control of rock breakers at multiple mines, increasing the operator's efficiency. A further benefit is that the operator can live comfortably in a city rather than in the harsh outback near the mines.

3.4 Military LLT

One of the biggest promoters for the development and the use of telepresence is the United States military. Telepresence is used by the military to enhance situational awareness with airborne drones such as the IAI RQ-2 Pioneer and GA MQ-1 Predator remotely piloted aircraft (RPA). Ground operations with remote-controlled robotic unmanned ground vehicles (UGVs) such as the small lightweight FM Talon, and the large (1500-lb. payload) M&Q Titan are also enhanced. Telepresence is achieved by using a wide variety of cameras including infrared and night vision, audio communications, and remote-controlled arms (Figure 3.6).

Figure 3.6: Talon tracked military robot (Image: U. S. Army. The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement).

Military teleoperated robots are used as replacements for soldiers in the field, in reconnaissance, and bomb identification and removal. Soldiers using LLT are able to act and receive real time information just as if they were present at the remote site without exposure to battlefield risks.

4. Established Modalities for Planetary Surface Exploration

During the last four decades, there has been a rapid development of technology to help us explore our solar system and search for worlds far beyond. We have developed impressive machines and tools that scientists can use to study in detail our small portion of the universe. While planetary surface exploration has progressed from flybys to orbiters to stationary landers to rovers, its key science aims are to understand and characterize the geology, mineralogy, internal structure, and atmospheric composition and dynamics of each body, preparing the way for in-depth investigations enabled by a human-robot sustained presence.

4.1 Human Presence: Apollo Lunar Surface Exploration

Our benchmark for human surface exploration performance on another world is the fieldwork performed by the six Apollo expeditions to the Moon's surface in 1969–72. Astronauts conducted geological field observations and collected samples during task-intensive EVAs—"moonwalks." The astronauts' performance was remarkable, motivated as they were by their limited lunar surface time; their scientific productivity surpassed that of terrestrial geologists who know they can always come back to the site tomorrow (Figure 4.1).

In their cumulative 12.5 days (25 man-days) on the lunar surface, the twelve Apollo moonwalkers traversed a total distance of 95.5 km from their landing sites (heavily weighted to the last three missions that were equipped with the Lunar Roving Vehicle). They collected and returned to Earth 379 kg of rock and soil samples (from over 2000 discrete sample localities), drilled three geological sample cores to depths greater than 2 m (plus another five 2–3 m cores for the heat-flow experiments), captured over 6000 surface images, and deployed over 2100 kg of scientific equipment (Crawford, 2012).

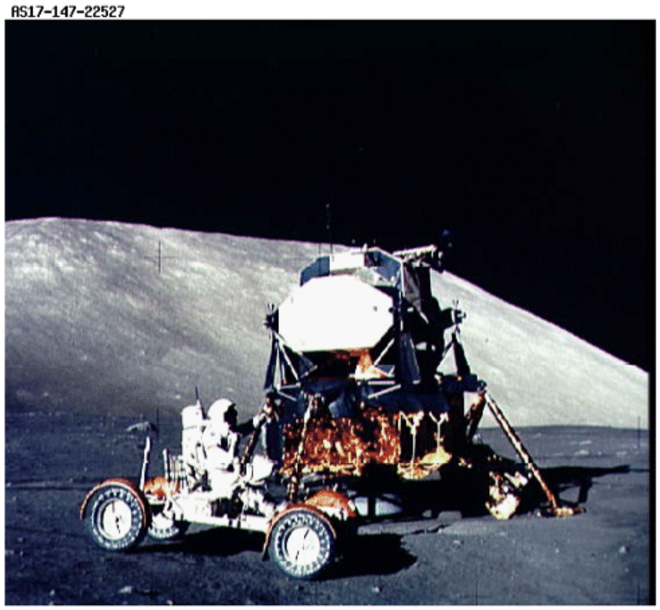


Figure 4.1: Astronaut Eugene Cernan, Apollo 17 mission commander, checks the lunar rover during the early part of the first extra-vehicular activity (EVA). The lunar module is in the background (Image: NASA).

The final three missions, Apollos 15, 16, and 17, were true multi-day field expeditions lasting a cumulative 219.5 hours (8.9 days) on the Moon. An approximate breakdown is illustrated in Table 4.1.

LLT can significantly increase the science productivity of future lunar or Mars surface exploration because the operators could work in shifts, reducing sleep period "losses." However, the habitat must be designed to insulate sleeping crews from noise and light, and the disruptions of shift operations to include audio communications with Earth-based mission control, intra-crew communications, and mandatory operations of exercise equipment. Astronauts aboard the ISS today have not adopted shift operations to increase science or maintenance productivity. Flight experience on the shuttle and ISS has shown that shift work decreases sleep quality, increases fatigue, leads to gaps in intra-crew communication, reduces opportunities for mentoring and handover, and lowers crew morale and cohesion (S. Wilson, 2019, personal communication). Increasing crew surface EVA frequency and productivity using multi-shift operations will suffer from similar drawbacks, added to the significant overhead losses from spacesuit donning, doffing, maintenance, and equipment staging tasks. Importantly, this split-crew paradigm may require a change in long-established emergency procedure response.

Operation	Number of Hours	% of Total
Science Operations Time (including rover traverses)	44.2	21
Logistics Time	92.5	43
Sleep Time	76.3	36

Table 4.1: Approximate breakdown of astronaut time on the surface of the Moon.

As noted by Eppler (1997), "The primary source of geologic data on the terrestrial planets is likely to be the collection of spatially based data on the distribution of rock units and structures." As in terrestrial field work, "future human missions to the Moon and Mars will rely heavily on geologic mapping to achieve science goals."

To enable such LLT mapping and field activities, remotely operated systems must give their operators wide-view, distortion-free observation of the terrain and the rock units, and provide the means for easy translation and the ability to reach and grasp. LLT-enabled rovers should enable access to the widest variety of terrain and geological formations possible. Lunar trials of such systems can be directly compared to the Apollo work results, pointing the way toward necessary improvements aimed at more distant terrain.

4.2 High-latency Telerobotics

4.2.1 Mars Rovers: Mars Pathfinder/Sojourner

Mars Pathfinder was a low-cost Discovery mission launched in December 4, 1996, and landed on Mars' Ares Vallis on July 4, 1997. The mission consisted of a lander and a small volume, lightweight 23-pound (10.6 kilogram), six-wheeled robotic rover named Sojourner (Figure 4.2), which became the first rover to operate outside the Earth–Moon system. Mars Pathfinder used an innovative method of directly entering the Martian atmosphere, assisted by a parachute to slow its descent and a giant system of airbags to cushion the impact.

Mars Pathfinder was originally designed as a "proof-of-concept" technology mission demonstrating a new airbag landing system designed to deliver a small science package, including a rover to the surface of Mars. Pathfinder not only accomplished this goal but also returned an unprecedented amount of data and outlived its primary design life. The rover UHF radio transmitted data to the lander for further relay by the lander to Earth.

Both the lander and the rover carried instruments for scientific observations and to provide engineering data on the new technologies being demonstrated. Included were scientific

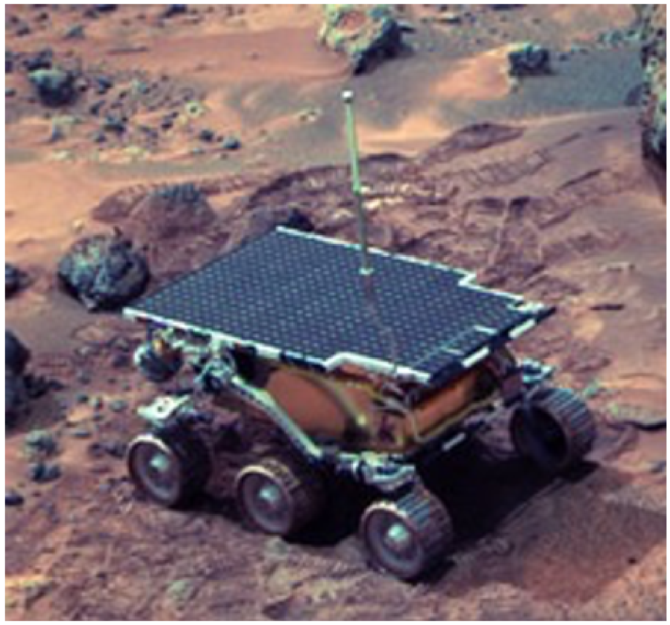


Figure 4.2: The 65-cm-long Sojourner Rover, part of the Mars Pathfinder mission (Image: NASA).

instruments to analyze the Martian atmosphere, climate, geology and the composition of the local rocks and soil.

Although the mission was planned to last from a week to a month, the rover operated successfully for almost three months. From landing until the final data transmission on September 27, 1997, Mars Pathfinder returned 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover, as well as more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors.

4.2.2 Mars Rovers: Mars Exploration Rovers Spirit and Opportunity

The Mars Exploration Rovers (MER) Spirit and Opportunity were twin rovers that landed in January of 2004 (Figure 4.3). The rovers had a mass of ~180 kg each, and were powered by solar panels that folded out after landing. Following the successful Sojourner example, the rovers used the successful six-wheel rocker-bogie suspension design and airbag landing system design.

The overarching goal of the MER mission was to "follow the water"—to identify and characterize geologic materials at two sites on Mars, searching for mineralogical evidence of past water activity (Squyres et al., 2003). Science instruments to meet those goals included the Panoramic cameras (Pancam) and navigational cameras (Navcam), and the Miniature Thermal Emission Spectrometer (MiniTES), all mounted on the rover mast. The rovers also each had an arm, with instruments mounted on it, for close-up examination of

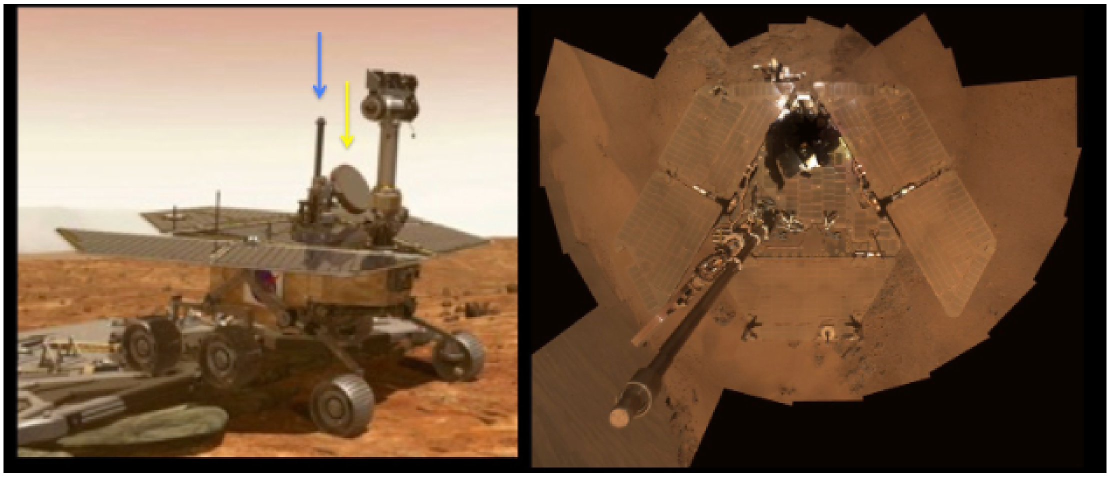


Figure 4.3: (left) Artist's conception of MER on Mars with the low-gain (blue arrow) and high-gain (yellow arrow) indicated. (right) Image mosaic of the rover deck acquired by Opportunity on sols 2811–2814.

surface materials. Arm-mounted instruments included the Microscopic Imager (MI), the Rock Abrasion Tool (RAT), the Mössbauer Spectrometer and the Alpha-particle X-ray Spectrometer (APXS).

Communication with Spirit and Opportunity was conducted through two high-latency paths: direct-to-Earth (DTE) and through orbiting assets such as Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY). The activities for anywhere from 1–4 Martian days (termed "sols") were uplinked from Earth to each rover during a single pass; the rovers would then perform the teleprogrammed commands in the uplinked plan, with navigation and hazard avoidance software providing some autonomous ability to avoid hazards. As part of each sol's plan, each rover would include one or more periods of time (orbital "passes") in which it would send data to an orbiting spacecraft as it passed overhead. That spacecraft would then downlink the data to Earth. Thus, a typical communications cycle with one of the MER rovers would include 1–2 windows for communication, each providing tens of Mbits of uplink volume from a rover. Less commonly, DTE communication was planned, specifically when data were needed rapidly on the ground, such as during anomaly resolution. Ultimately, >135 Gbits of data were transmitted in this manner over Spirit's lifetime, while >270 Gbits of data were received from Opportunity. These high-latency communications constraints limited the amount of science data returned to Earth.

Spirit and Opportunity were designed around a nominal mission lifetime of 90 Martian days, but lasted for years (and in the case of Opportunity, over a decade). Spirit sent her last communication on March 22, 2010, after struggling for months to be extricated from sandy soil. The last communication from Opportunity came on June 10, 2018, with mission end the result of a planet-encircling dust event that blotted out the Sun upon which the rover depended for power.

4.2.3 Mars Rovers: Curiosity

The Mars Science Laboratory (MSL) rover Curiosity (Figure 4.4) landed in Gale Crater August of 2012. Like its predecessors, Curiosity utilized the six-wheel rocker-bogie suspension design with independently actuated and geared wheels, though the wheels were larger (50-cm diameter versus 25 cm for MER and 13 cm for Sojourner). Unlike the three earlier rovers, however, Curiosity's mass (~900 kg) made an airbag landing impractical, and instead the mission used a combination of traditional retrorockets coupled to a "sky crane" system that lowered the rover from the descent stage to the surface with a 20-m tether. Curiosity thus became the first rover to touch down directly on its wheels. The original mission concept was to bring laboratory-style instruments to Mars, to conduct more in-depth analysis on samples than had been previously possible, thus increasing rover mass and power requirements. These instruments demanded more power than solar panels could supply, so like the Viking landers, the rover is powered by a radioisotope thermoelectric generator, which supplies ~2.5 kWh per day, compared to ~0.6 kWh supplied by the MER solar panels. The MSL mission is still active as of this writing, seven years into its second mission extension.

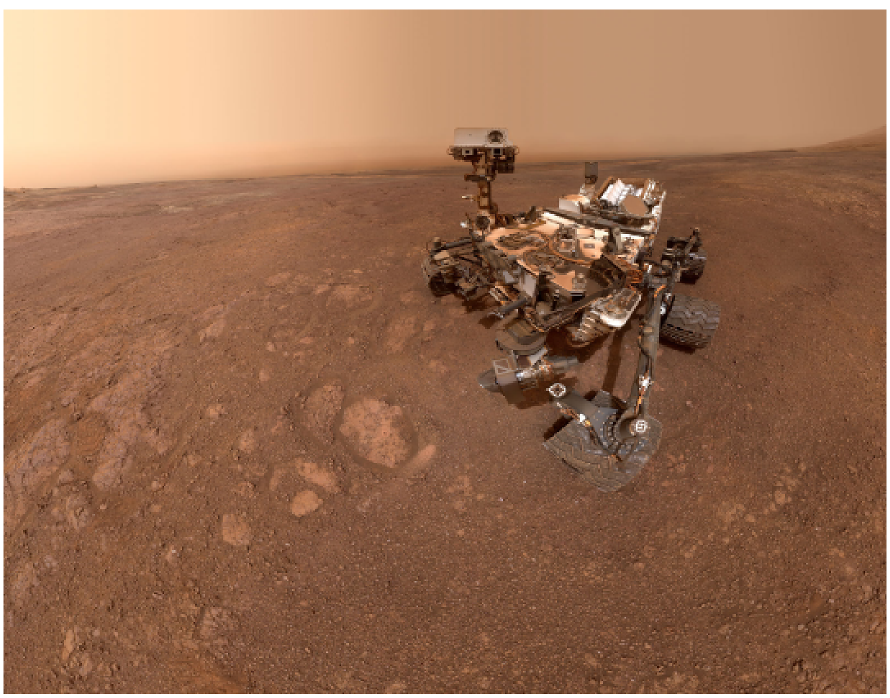


Figure 4.4: Self-portrait mosaic of Curiosity rover acquired by the MAHLI camera on mission sol 2291. Image: NASA/JPL-Caltech/MSSS

Mars Science Laboratory was designed to help determine whether Mars could ever have supported life; to better understand the role of water in Martian history; and to study the current Martian climate and its past and present geology. To meet these goals, the rover carries three categories of instruments: those designed to gather data remotely from the rover mast; those designed to acquire data close to the surface by deployment from the rover turret (arm); and those within the rover body, designed to process and analyze samples (Grotzinger et al., 0025). The first category includes the Mastcams (two cameras at different focal lengths for higher resolution or wider field-of-view imaging) and navigational cameras, the Remote Environmental Monitoring Station (REMS) designed to observe the atmosphere, and the ChemCam (a laser-induced breakdown spectroscopy [LIBS] instrument combined with a remote micro imager [RMI]). The second includes the Mars Hand Lens Imager (MAHLI) and like MER, an Alpha-Particle X-ray Spectrometer (APXS), as well as a Dust Removal Tool (DRT) to support these instruments by cleaning off some of the ubiquitous mantling Martian dust. In the last category are the Sample Analysis at Mars (SAM) and the Chemistry and Mineralogy (CheMin) instrument.

Like the MER rovers, high latency (as shown in Figure 4.5) demands that MSL communicates data either through DTE or through orbiting assets, which currently include MRO, ODY, MAVEN and ESA's ExoMars Trace Gas Orbiter (TGO). All of the current orbiters are missions in their own right and there is no orbital asset devoted solely to rover communications. Each orbiter is only able to communicate with the rover for a few minutes per sol, and the data volume allocated to the rover for each pass must be balanced by the data the orbiters themselves must downlink to Earth to meet their own mission objectives. As was true for MER, activities for anywhere from 1–4 Martian days are uplinked from Earth during a single orbiter pass; however, Curiosity is able to process significantly more data volume than were the MER rovers—hundreds of Mbits per pass.

4.2.4 Hayabusa: Semi-Autonomous Science Near a Small Asteroid

Launched on May 9, 2003, the Hayabusa spacecraft (originally named MUSES-C) arrived at the near-Earth asteroid (25143) Itokawa in September 2005. During the next 10 weeks, Hayabusa conducted autonomous observations of Itokawa to determine the asteroid's shape, terrain, mineral composition, gravity, and albedo variations. On November 25, 2005, Hayabusa performed autonomous landing operations on Itokawa to obtain a surface sample for return to Earth.

During landing operations, Hayabusa attitude control and communications with Earth were lost due to a propellant leak and malfunctions in two of three reaction wheels; light-time delays prevented immediate troubleshooting and intervention by the ground. Recovery operations began with Hayabusa commanding on January 23, 2006 and continued into May of 2006. These actions necessitated Earth return postponement from 2007 to 2010 with Hayabusa

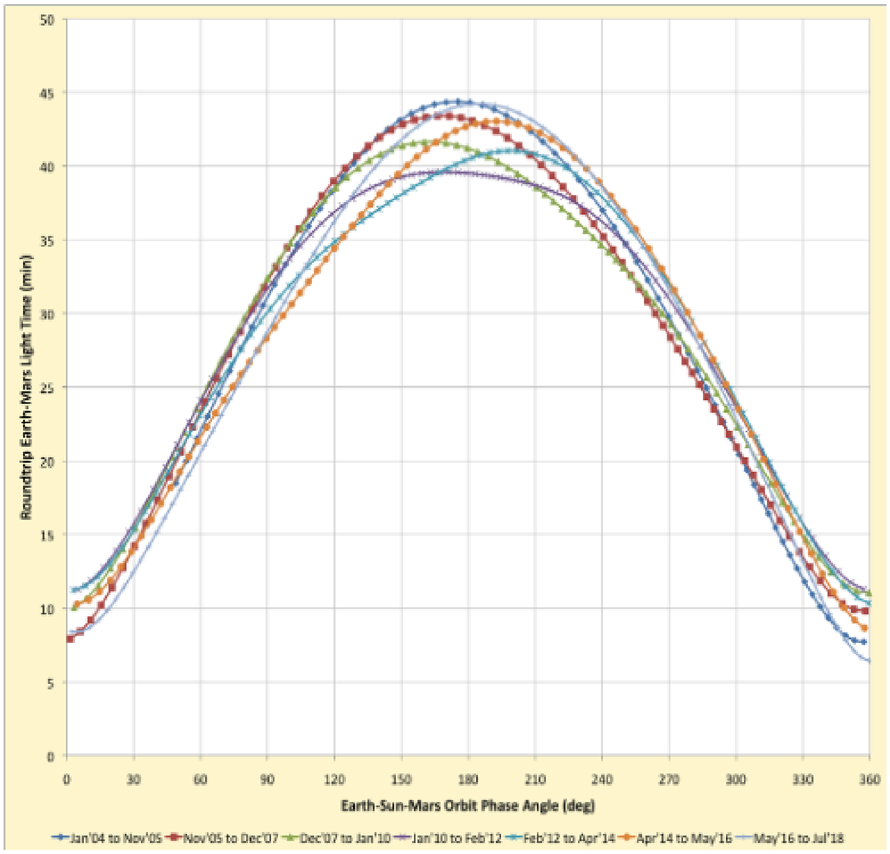


Figure 4.5: Round-trip light time between Earth and Mars for the time period of active Mars rover missions (up to July 2018).

departing Itokawa in April 2007. Unavoidable Hayabusa data latencies imposed by round-trip light time to Earth during science and mission recovery operations are plotted in Figure 4.6.

During an Itokawa landing rehearsal on November 12, 2005, commands to deploy the Micro-Nano Experimental Robot Vehicle for the Asteroid (MINERVA) lander were transmitted too late. By the time deploy commands were received by Hayabusa, the spacecraft had autonomously reversed its descent after reaching closest approach to Itokawa of 44 m. Consequently, MINERVA's imparted trajectory carried it clear of Itokawa without ever landing, and its science objectives were left unfulfilled.

4.2.5 Rosetta and Philae: Autonomous Science from a Comet's Surface

Launched on March 2, 2004, ESA's robotic Rosetta spacecraft arrived at comet 67P/Churyumov–Gerasimenko on August 6, 2014. After establishing orbit 10 to 30 km from the comet, Rosetta deployed its Philae lander module on November 12, 2014.

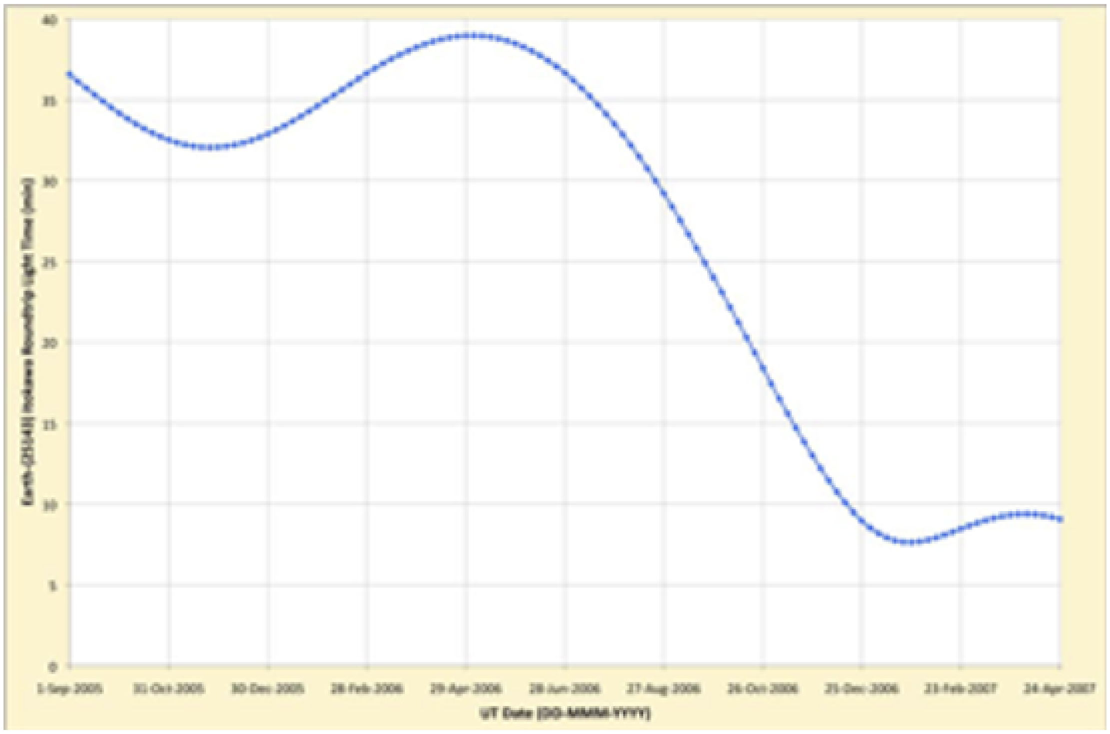


Figure 4.6: Round-trip light time between Earth and (25143) Itokawa is plotted as a function of UT calendar date during the interval Hayabusa was proximal to this asteroid.

On initial touchdown, Philae was to have fired harpoons into 67P, anchoring the lander in place. When these firings failed, communications latency with Earth (see Figure 4.7) prevented any corrective action from being taken. Bouncing after initial touchdown, the lander drifted in 67P orbit for two hours. Philae touched down and rebounded once more before coming to rest on the comet.

However, the lander's uncontrolled touchdown left it in a position with insufficient solar illumination to power its systems (Figure 4.8). The module's batteries discharged after three days on the comet, and communications with Philae were lost. Fragmentary communications with Philae were restored in June/July 2015 near 67P perihelion as solar illumination increased. Although some science data were obtained from Philae, they were significantly curtailed by insufficient solar power. Philae's actual landing site was located only after Rosetta obtained close-range imagery of 67P on September 5, 2016.

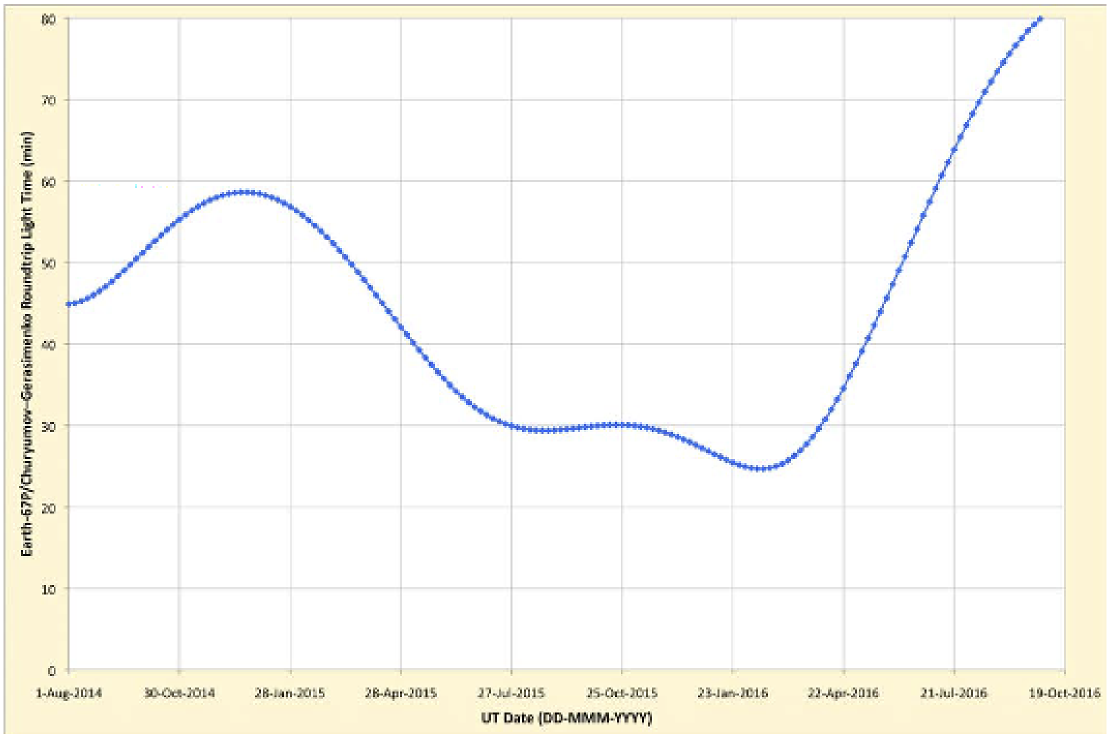


Figure 4.7: Round-trip light time between Earth and 67P/Churyumov–Gerasimenko is plotted as a function of UT calendar date during the interval Rosetta operations proximal to this comet were conducted.

4.3 Moderate-Latency Teleoperation

4.3.1 Lunokhod

In the early 1970s a pair of Soviet-built Lunokhod rovers explored the lunar surface, a robotic component of the Soviet Union's manned lunar exploration program. The two Lunokhods were controlled from Earth in near-real time by teams of operator-drivers.

The Lunokhod 1 rover was delivered to the lunar surface on Nov. 17, 1970 by the Luna 17 spacecraft, and survived until Sept. 14, 1971, the first successful rover to operate beyond Earth. In 322 Earth days, it traveled more than 10 kilometers across the lunar surface, during which it transmitted more than 20,000 TV images and 206 high-resolution panoramas, performed 25 soil analyses with its spectrometer, and used a penetrometer to test the soil's mechanical characteristics at more than 500 locations. Lunokhod 1 also carried a laser retroreflector which enabled precise measurements of the Earth–Moon distance to within about 30 centimeters.

The Lunokhod 1's rover's top speed was a little over 100 meters per hour, with commands issued by a five-man team of "drivers" on Earth. Teleoperation at low latency was limited to

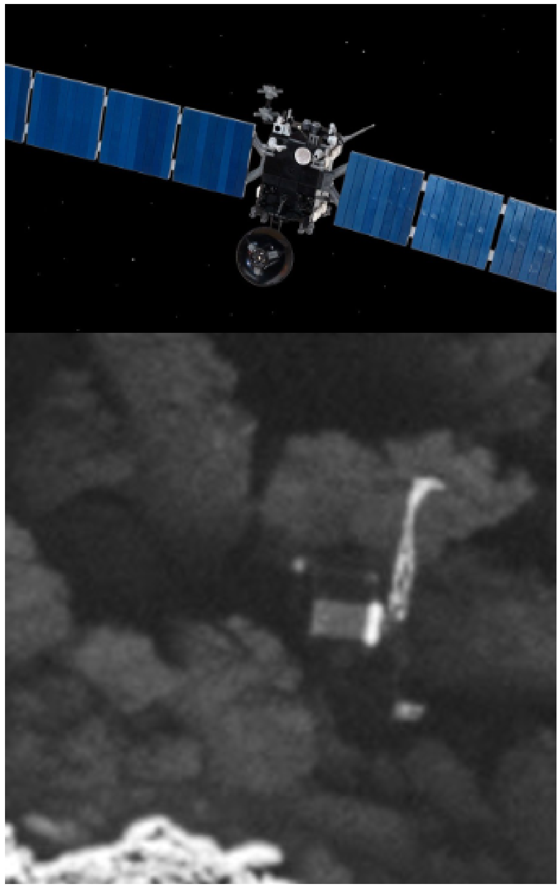


Figure 4.8: (Top) Artist's rendition of the Rosetta spacecraft. (Bottom) Philae lander after failed controlled landing attempt (Images: ESA).

driving commands by using TV sensors to access the terrain. Operators contended successfully with a 5-second communications delay. Science operations were commanded only while the rover was stationary.

Lunokhod 2, which landed on Jan. 8, 1973, was equally successful. By the end of its first lunar day (about one Earth month), Lunokhod 2 had already traveled farther than Lunokhod 1 in its entire operational life. Overall, it covered 37 kilometers of terrain, including hilly upland areas and rilles, transmitted 86 panoramic images and more than 80,000 TV pictures of the lunar surface, and conducted at least 740 mechanical tests of the soil. The laser ranging experiment again enabled precise measurements of the Earth–Moon distance.

The small but noticeable round-trip communications delay contributed directly to Lunokhod 2's demise. On May 9, the rover inadvertently rolled into a crater and dust thrown up by its wheels disrupted thermal controls. The mission concluded after four months of operations on May 9, 1973. Although the Lunokhods lacked manipulator arms or 3-dimensional, high

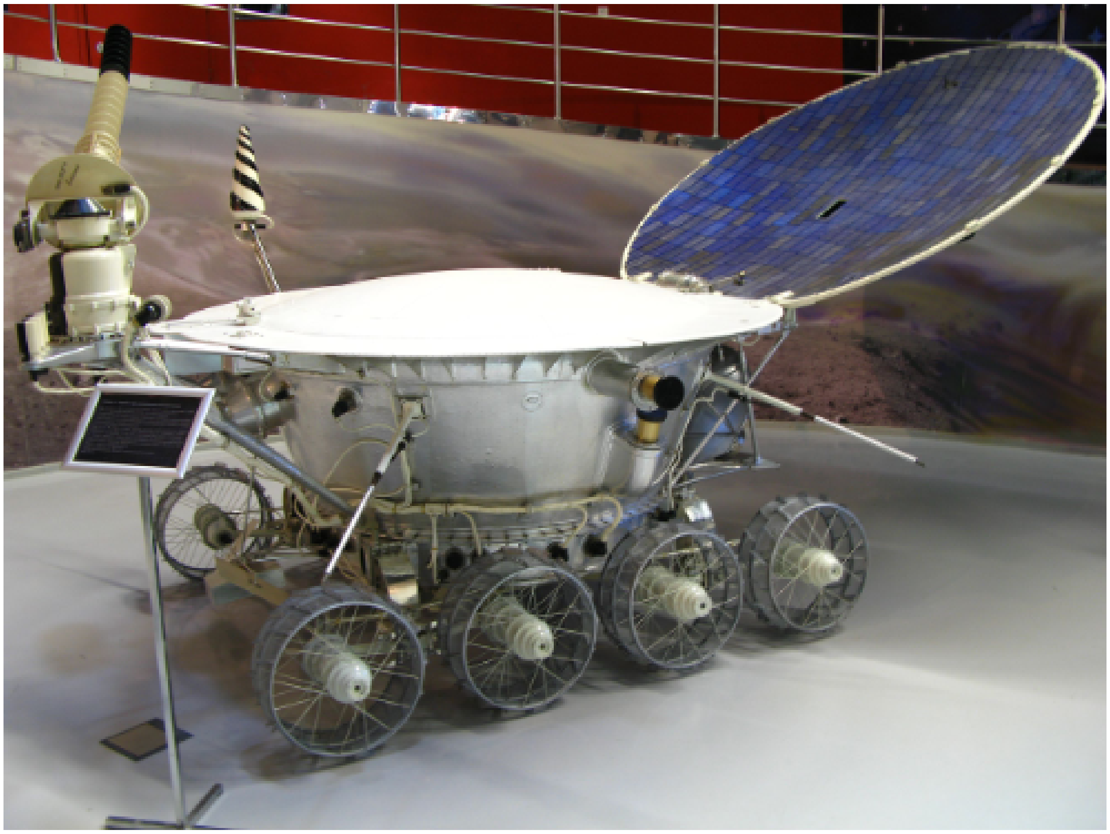


Figure 4.9: Soviet lunar rover Lunokhod 1. The spacecraft soft-landed on the Moon on November 17, 1970 (Image: Roscosmos).

fidelity imaging systems, their success hinted at the potential for advanced rovers to exploit low-latency telepresence for sustained surface science operations.

5. Low-Latency Telepresence as an Augmenting Strategy

Present long-term planning at NASA is primarily focused on landing astronauts on the Moon in the 2020s, followed by human missions to Mars and other destinations (Space Policy Directive, 2017; see Chapter 8 for more detail). The first stage in future human exploration to any planetary body (e.g., Moon or Mars) for safety, engineering, and cost considerations ideally involves a crewed orbiting mission with the deployment of robotic surrogates to the surface. An orbital mission provides a good shakedown of the spacecraft and enables reconnaissance of the planetary environment through deployment of robotic assets. These assets not only provide the means for astronauts to prepare for eventual surface exploration missions, but also to continue to work efficiently through these assets after landing. The pre-landing orbital operations will help refine the human and robotic interactions, and provide the detailed knowledge necessary to choose a site for a surface habitat and operations base. After robotic agents provide initial field reconnaissance, humans will guide the field campaigns using LLT; tasks will include geological mapping, synthesis of observational information, interpretations, and planning and continued reconnaissance (Figure 5.1).

In conventional robotic missions, the high-latency exchange between terrestrial humans and robotic explorers is predominantly one-sided and slow: humans dictate the movement and activities of the robotic assets at significant cost in time, money, and inefficient expenditure of the lifetime of the deployed hardware, resulting in limited science return. In conventional crewed missions, EVAs are hazardous and limited by the energy toll on the astronauts who work encumbered by spacesuits. LLT alters these paradigms, overcoming the present substantial communication lags of robotic missions, while multiplying the effectiveness of the astronauts working from within a safe environment for crewed missions. Both orbiting humans and landed

Figure 5.1: Interior view of an astronaut controlling a robotic asset on the surface of Mars. White overlays illustrate the rotational movement of the astronaut's hands. (Image: Keck Institute for Space Studies [KISS])

crews who direct robotic field agents result in exploration of substantially higher quality and greater science return—"more bang for the buck."

5.1 Motivation

5.1.1 Mission Risk and Cost Reductions Enabled by LLT

Employing LLT to enable humans to explore solar system objects substantially reduces mission risk. Telepresence activities, conducted by astronauts from a safe, shirt-sleeve environment, replace high-risk EVAs, where astronauts on the surface are exposed to physical and environmental hazards. LLT also allows for exploration of locales that are dangerous to traverse, yet are of significant scientific interest (e.g., steep terrains, caves, etc.). Astronauts can conduct LLT exploration not only from subsurface outposts, but also during the approach, orbit, and return mission phases.

Notably, LLT also enables human orbit-only precursor missions to deliver significant surface science return without the risks and cost of landing. Conventional astronaut surface expeditions require a human-capable descent and ascent stage, surface habitat, power systems, and ideally a pressurized rover. On the other hand, telepresence robotic surrogates and their landed support systems are markedly less massive and complex. In advance of careful cost estimates, it can still be assumed that the cost of sending humans into orbit around Mars will be a small fraction of that required to land them, support them on the surface, and lift them from Mars. Informal industry estimates suggest that a humans-to-Mars-orbit campaign will cost about half that of taking astronauts all the way to the surface—and back (see Section 2.4).

The degree of value for LLT depends partly on the answers to questions about campaign risk posture, resources, and requirements:

1. What activities or tasks are preferable to conduct prior to crew landing to help reduce on-surface risks and workload?
2. What is the value of reducing the risks associated with EVA such as radiation exposure?
3. What risk-reduction tasks should be performed by traditional high-latency semi-autonomous methods from Earth? What is the likelihood of completing those tasks prior to crew arrival and/or landing?
4. To what degree will LLT shorten timelines and contribute to greater science productivity?
5. Which tasks should be conducted via LLT as the primary operations mode?
6. Are the hardware and resource costs (e.g., mechanisms, consumables, power) for conducting surface tasks via LLT less than those required by crews on the surface?
7. How are risks and costs reduced by doing in-situ site assessment and validation using LLT?
8. How effective is it to do in-depth surface science prior to crew landing? Or, can we perform extended in-depth field exploration using LLT prior to our readiness for human arrival?
9. Will it be effective to search for and explore regions with planetary protection issues using LLT prior to landing crew?
10. Will LLT aid in sample containment, inspection, and isolation prior to any crew involvement with sample return to Earth?

Answers to the above questions will clearly illustrate the value of LLT. Evaluation of LLT should be part of a comprehensive risk analysis for any human exploration campaign and its goals.

There are numerous LLT tasks envisioned at Mars that would benefit from high-fidelity space-based rehearsals from the ISS and in cislunar space. Some progress toward these LLT operations tests is already being made (see examples in Bualat et al., 2014; Fong et al., 2014; Nergaard, de Frescheville, et al., 2009; Schiele et al., 2016; Thronson et al., 2014; see also Chapter 8).

A notable example is positioning crew at an Earth–Moon Lagrange point (Lester et al., 2012) or in lunar orbit to acquire lunar samples via LLT. This human supervision may return much larger and selective sample quantities compared to robotically returned samples (Burns et al., 2013).

5.1.2 Latency Variation Based on Spacecraft Distance from Destination

During interplanetary transit, as astronauts become more proximal to landed assets and latency decreases, remote operations from their spacecraft become progressively more efficient. This "efficiency spectrum" is illustrated in Figure 5.2 along the "Spacecraft <—> Mars" latency plot as it progresses from red to green at "Arrival." In the same way, during crew return to Earth, remote operations through landed assets also become less effective after departure. The landed robotic assets will continue to be utilized using conventional high-latency, teleprogrammed control from Earth when no astronauts are nearby, thus further extending their usefulness.

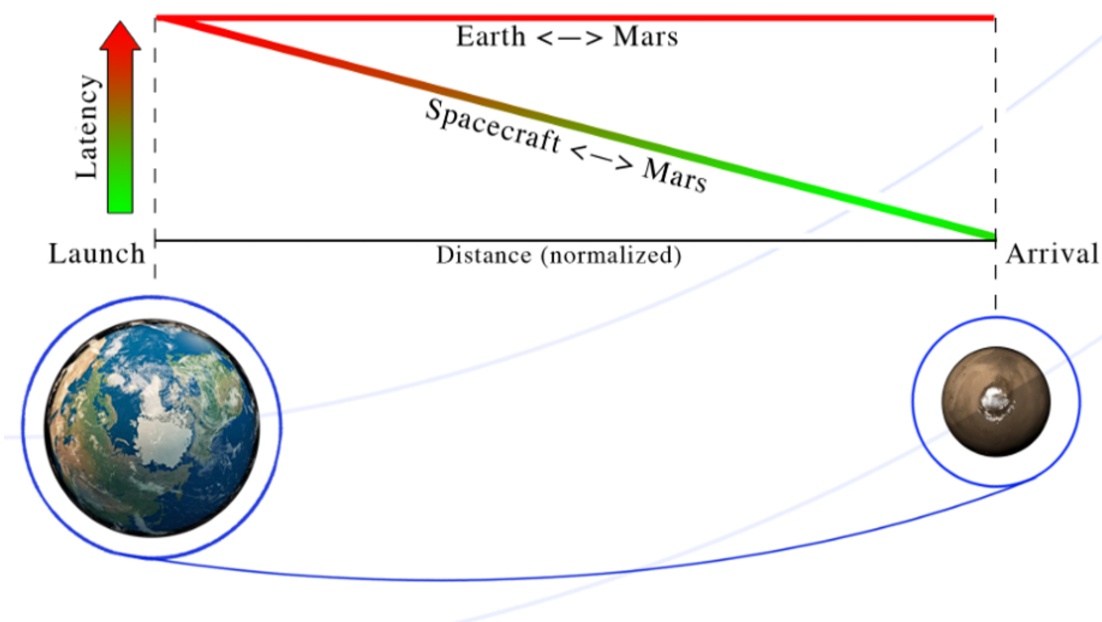


Figure 5.2: Mars latency plot as the spacecraft progresses from red (high latency at Earth departure) to green (low latency at Mars arrival) (Image: G.Podnar).

5.2 Proposed Use Cases

5.2.1 Planetary Field Geology

Field geology is the practice by which scientists collect direct observations of landscapes, rock outcrops, and in-situ samples to understand the formational history of a field site. A geologist's ability to identify the geometric and structural relationships amongst all the landscapes is required to determine the spatial and temporal history of the features and the conditions or processes that existed when they formed (Figure 5.3).

Figure 5.3: Mars Science Laboratory micro-imager view of Vera Rubin Ridge (Image: NASA/JPL/MSSS).

Planetary field geology is a significant contributor to understanding the formation of the Earth and the solar system. Conducting field geology on other planetary bodies requires the use of advanced technologies to provide the data necessary for a field geologist to conduct scientific studies of these very distant planetary field sites.

For example, the way field geology is currently conducted on Mars is by collecting in-situ data from remote probes and surface rovers. The science data returned to Earth are restricted and inhibited by long communication delays between the Earth and Mars. When Apollo 17 landed a field geologist on the Moon, the geological science data returned was increased substantially because the scientist was present at the field site. This will also be true for other planetary bodies. In the same way it was necessary to have a planetary field geologist present on the Moon, it will be necessary for scientist/astronauts to be present to result in similar science data return as the Apollo mission.

The costs and risk of putting field geologists on a planetary surface in space suits is very high. Minimizing the exposure of the astronauts to the environmental conditions reduces their risks while increasing their efficiency. When field geologists are nearby, whether in a landed or orbiting habitat, employing LLT technology will allow them to conduct in-situ observations and sampling while minimizing their risks and the crew timeline-overhead to prepare for and secure from EVA. This also applies as they are approaching; orbiting before landing; and while outbound returning to Earth. The telerobotic sensory fidelity, dexterity, and mobility, combined with the immediacy provided by effective LLT technology, will contribute substantially to field geology and other scientific research on planetary surfaces.

5.2.2 Unique Science: Inaccessible Places

In addition to putting humans into direct contact with the surface environment remotely, LLT is a strategy to put human real time presence where we simply cannot or should not put humans. For example, human presence could be put real time on steep Martian slopes; inside deep crevasses or lava tubes (Figure 5.4); on the surface of Venus; or under a methane lake on Titan. LLT can also deploy human presence without the biological contamination due to an astronaut presence. And beyond the Moon and Mars, LLT is a strategy that will greatly expand the reach of human presence in the solar system.

Figure 5.4: Stefánshellir cave Iceland, a terrestrial lava tube (Image: `https://www.extremeiceland.is/de/aktivtouren/hoehlenwanderung/surtshellir-hoehle`).

5.2.3 Enabling Timely Real Time Observations Using LLT

Sometimes geological events happen on a relatively rapid timescale. In situations where transient geological events happen quickly, LLT may provide the scientist the ability to rapidly respond in real time. On Mars, for example, rapid observation of events such as landslides, dust devils, dust storms, clouds, and meteorite impacts would provide scientists with valuable information on these events.

Recent studies have demonstrated the possibility of fluvial activity taking place on the Martian surface. Due to the atmospheric conditions, these transient features, called Recurring Slope Lineae (RSL; Figure 5.5), are believed to form very quickly (within minutes). Not only could these RSL events be observed in real time using LLT, but it would enable scientists to sample these fluids before they disappear. LLT-based analysis could enable scientists to make real time decisions and tactical changes that cannot be done by HLT stationary landers or rovers. LLT can also provide real time observations of erupting plumes on Saturn's moon Enceladus, geysers on Jupiter's moon Europa and Neptune's moon Triton, and volcanic activity on Jupiter's moon Io. In addition to the real time observations of transient phenomena, LLT would enable timely analysis of in-situ samples.

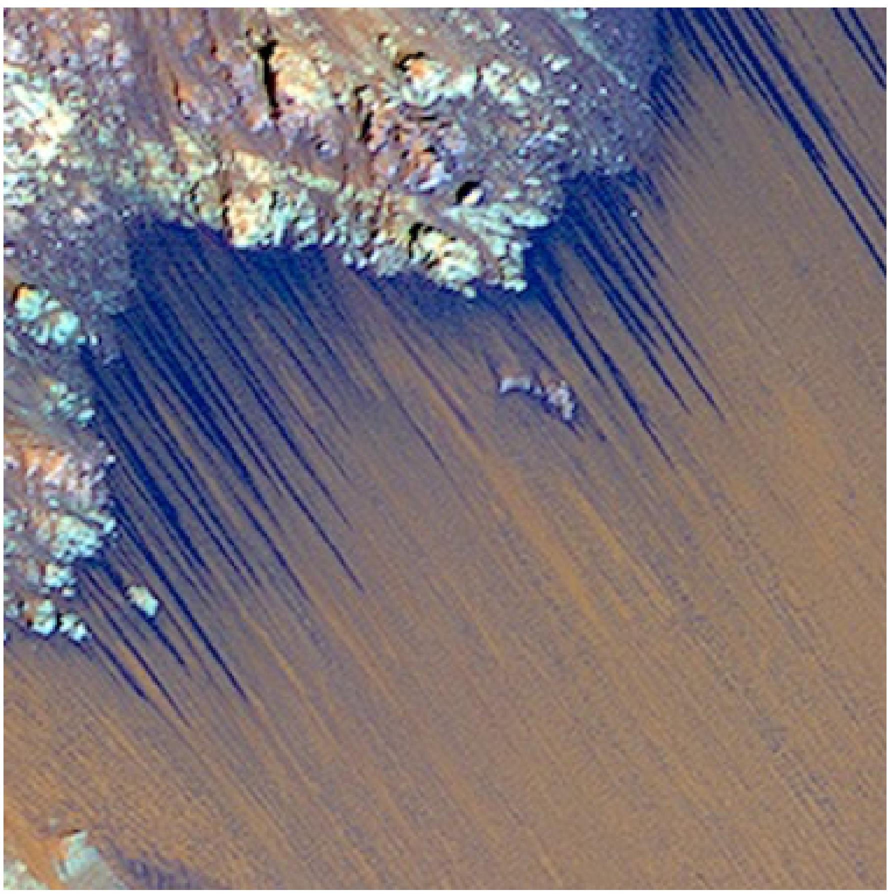


Figure 5.5: Seasonal flows on warm Martian slopes are thought to be salty water flows occurring during the warmest months on Mars, or alternatively, dry grains that "flow" downslope (Image: NASA).

5.2.4 Science Enhancements Using LLT

One of the advantages of LLT is the ability for astronauts—in protected orbital or surface habitats—to enhance the science return via real time decision-making. For example, if one of the remote robotic assets identified something unusual or unexpected, the astronaut could make a real time adjustment based on the new science data. In one scenario, a HLT rover, instructed to drive 25 m, might bypass a target of interest (e.g., mud cracks or a dinosaur bone; see Figure 5.6), and neither collect nor relay the data to Earth as images. If the data were accidentally acquired, the scientist would not see them until long after the rover had driven past the target. These lost opportunities have been a major concern during the MER and MSL operations. Using LLT, the astronaut/scientist would have both the information and the flexibility to determine whether or not to abort the sequence and examine the new target.

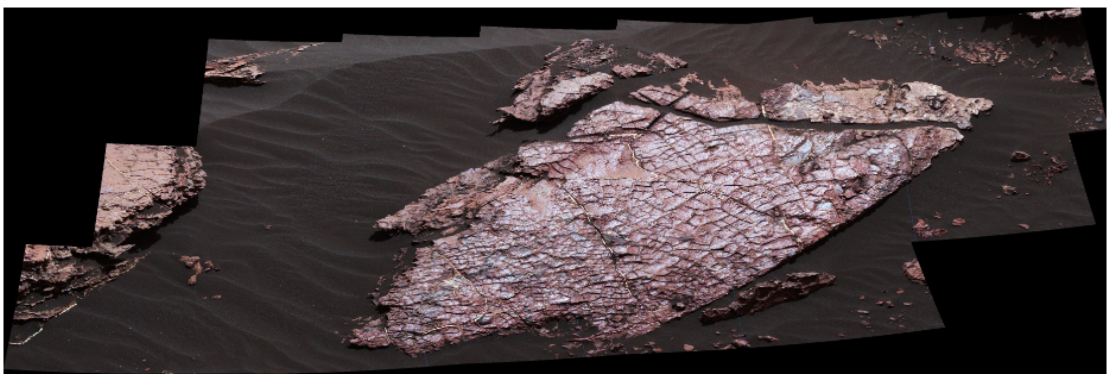


Figure 5.6: Mudcracks identified by the Mars Science Laboratory rover at Gale Crater (Image: JPL/NASA/MSSS).

Another advantage of using LLT is the ability to conduct broad site surveys. The Spirit, Opportunity, and Curiosity rovers have demonstrated the capability of doing long traverses. Although mobility is the prime attribute of a rover, its long traverses may cause scientists to miss changes in the surface geology, such as crossing a geologic/rock boundary. Real time LLT sequence modifications enable scientists to absorb a broader view. This enables the scientist to perform real time geologic mapping as well as to manipulate targets within the rover's reach.

5.3 Off-Earth Architecture Synergies from Low-Latency Telepresence

The same infrastructure enabling LLT planetary field geology possesses an inherent ability to perform other vital off-Earth tasks. For example, prior to any human resident's arrival and occupancy, construction of subsurface habitat, and support facilities is enhanced by LLT. Following crew arrival, LLT will continue to support surface operations by robotic proxy, thereby reducing crew exposure to harmful radiation and other risks such as EVA suit failures.

Increased productivity of surface tasks via LLT (eliminating EVA overhead, constraints, and stresses) will likely increase crew morale. This productivity is realized for both planetary science or interplanetary civil engineering.

5.3.1 LLT Use Cases in Addition to Geological Scientific Exploration

Systems required to conduct planetary field geology via LLT include communications, robotic digging tools, sampling systems, and assay instruments. These systems will also support other tasks such as setting up surface equipment, construction of infrastructure, and in-situ resource utilization (ISRU).

As an example, when ISRU is part of a mission design, there can be a shared purpose between geologic survey traverses and prospecting for ISRU essentials such as water. All mobile robotic assets, no matter what their task specialization, will ideally also be scientifically capable machines.

A commonality between field geology and ISRU is burying a habitat under a regolith layer to provide adequate crew radiation shielding (Figure 5.7). More refined ISRU products, such as propellant, will require larger processing and storage facilities than those used for field geology. The emplacement and commissioning of these facilities will again entail use of the same equipment used to construct habitat infrastructure. And with LLT in support, humans need not be onsite to supervise this construction.

Figure 5.7: Artist's conception of a future lunar base and operation center. Habitat is buried under regolith to protect from radiation. (Image: ESA / Foster + Partners).

Prospecting and construction activity enabled by LLT can be far more extensive (spatially and temporally) than what would be the case via EVAs. Successful prospecting for these resources could substantially increase consumables for habitats, transport vehicles, and other systems required for crew survival and science data return. Unanticipated resource discoveries could also open up unexpected avenues of interplanetary commerce. (See more details on plans for off-Earth mining and resource extraction in Section 8.5).

5.3.2 LLT and Human Factors

Imagine astronauts transported into orbit around Mars after an outbound journey lasting the better part of a year (Figure 5.8). Because they arrive well after the optimal departure date for Earth return, these astronauts must remain in the vicinity of Mars for about 1.4 years before return can be initiated. If this crew cannot land on Mars (either by design or circumstance) or if an abort to orbit is necessary after only a short surface stay, mission science return would be disastrously curtailed without the availability of LLT. Furthermore, LLT activities on Mars are practical before arrival at and after departure from Mars orbit.

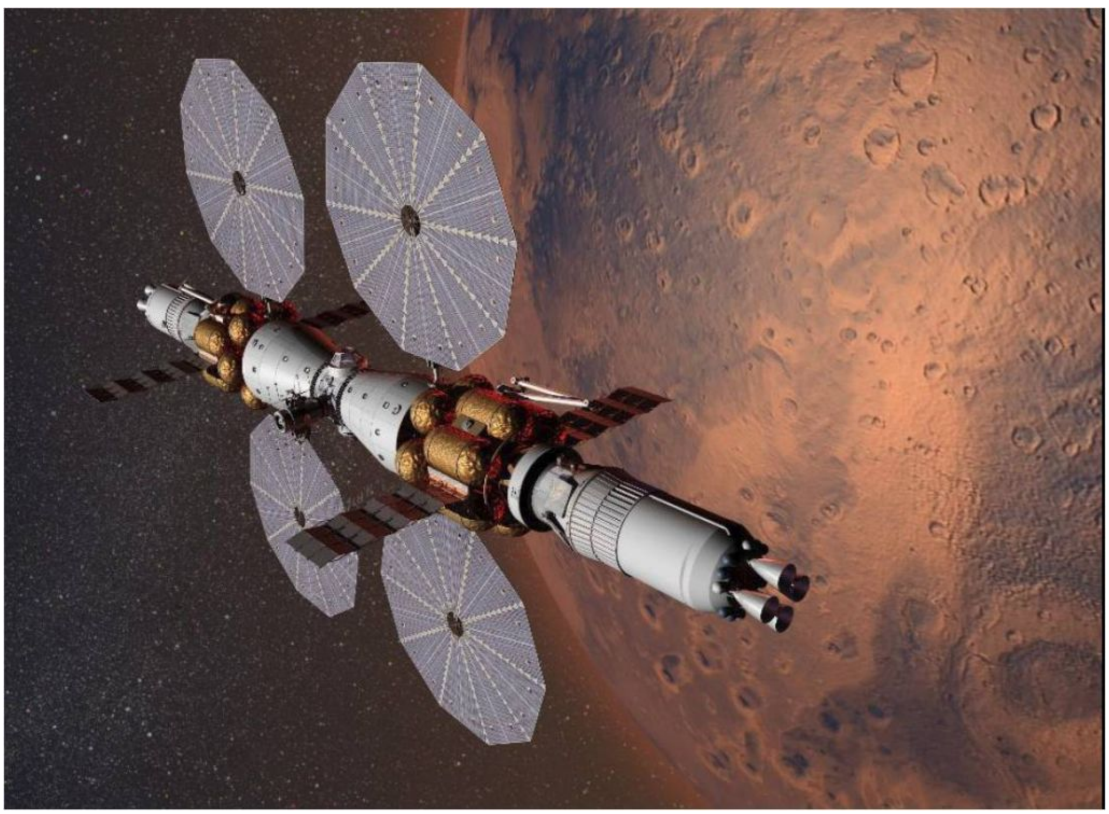
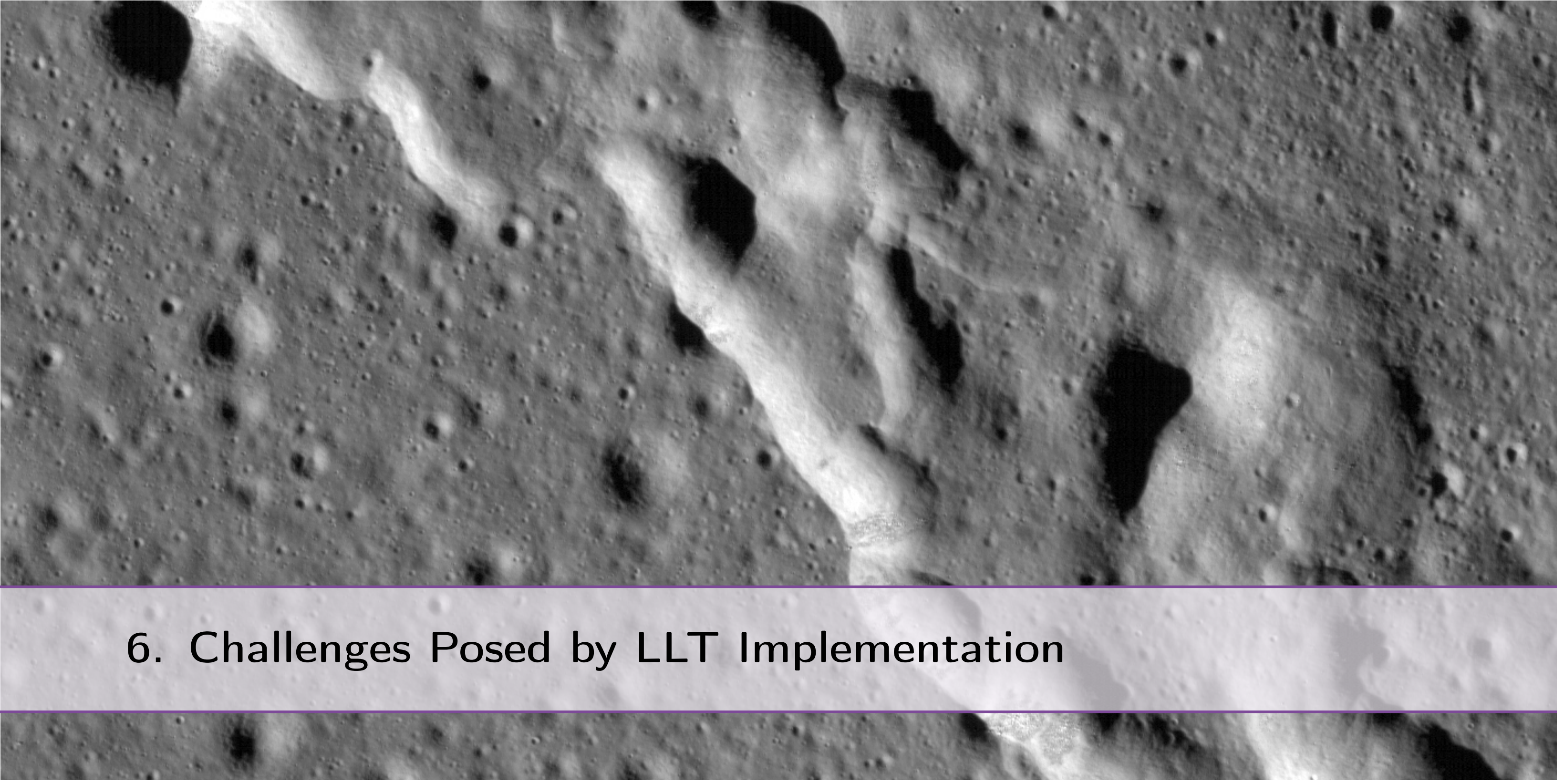


Figure 5.8: Artist's concept of Mars Base Camp, a proposed space station that could be circling the Red Planet by 2028. (Image: © Lockheed Martin)

Based nearly full-time in an LLT-enabled habitat insulated from radiation, toxic or abrasive dust, vacuum, a suffocating atmosphere, unstable terrain, or temperature extremes, crew stress will be reduced compared to astronauts with regular surface EVA assignments. It may also be possible to reduce the dangers of dynamic powered flight regimes far from Earth should LLT permit fulfilling mission objectives without humans landing at and launching from an exploration destination deep in a gravity well.



6. Challenges Posed by LLT Implementation

To implement LLT for planetary science exploration, it is necessary to characterize the science, engineering/technical, and operational challenges. This includes identifying and addressing these challenges and their required resources. Space science destinations have different requirements; for example, an asteroid may need very different exploration techniques than a planet or moon. Each destination requires technology to be tailored and validated specifically for it.

6.1 Science Challenges

6.1.1 Assessing Science Efficiency of LLT versus EVA

Advancements in science are achieved by identifying questions and applying established proven methods or developing new methods. Science efficiency is a measure of how much scientific return is gained from a process. Comparing the effectiveness of exploration via EVA or through LLT will show the advantages of science efficiency and identify the comparative risks for each method. Understanding what types of terrestrial field studies, laboratory experiments, and computer model simulations are needed to assess the science efficiency and value of using LLT is an important requirement for conducting planetary geological field work. It is crucial to determine whether the data needed to validate science efficiency can be obtained on Earth, in space, by analog, or via direct measurements.

6.1.2 Conducting Wide-Area Mineralogic Surveys via LLT

In addition to the scientific exploration of a destination's geology, LLT can be used in performing ISRU activities. LLT will first be used to collect relevant data regarding the locations of useful deposits prior to the landing of astronauts. Satellite surveys are insufficient for the detailed prospecting needed to be accomplished on the surface. Research is needed on how to employ LLT for wide-area mineralogical surveys (Dolan et al., 2005) and in-situ sample analysis for ISRU programs.

6.1.3 Incorporating Autonomy into LLT Tasks

The addition of robotic assets to human missions supports a co-robotic architecture where human activities can be augmented by intelligent agents (Dolan et al., 2005). For field geology and other use cases (identified in Sections 5.2 and 5.3), intelligent software agents can be developed to offload the human operators from some of the more mundane tasks. For example, mobile traverses may incorporate significant autonomous mapping and navigation. This allows the astronauts to focus on the difficult decisions and tasks for which autonomous agents are limited.

Research is necessary to classify which robotic systems may realistically include autonomous agents. As LLT systems are deployed, such as from the Lunar Gateway (see Section 8.1), a co-robotic architecture that supports multi-level autonomy will aid in developing and commissioning autonomous agents. This allows formal assessment of the degree to which these agents will be given control, the level of supervision required, and the statistical frequency of intervention needed by the human operators.

The communication latency possible between the Earth and Moon (2.5 seconds minimum round trip) may enable stepwise development, testing, and optimization of lunar robotics systems for exploration and other tasks. When humans are present at the Lunar Gateway, LLT activities will be conducted in near real time, gaining operational knowledge and experience.

Mission planning and task completion assessments will characterize the tasks which can operate largely autonomously, the tasks that can safely await delayed human intervention, and those tasks that will require real time supervision or direct teleoperated control. Proving these systems at the Moon will feed forward to techniques on other celestial bodies (i.e., near-Earth asteroids and Mars).

6.2 Engineering/Technical Challenges

Identifying mature and nascent technologies, along with the best practices applied to ongoing commercial and scientific applications of LLT, will be necessary to define the development and integration to achieve the exploration and science task requirements.

The required areas of technology development and testing will be primarily determined by identifying the multi-sensory telepresence, remote control, and tele-manipulation tools that are required to accomplish the planned science and exploration tasks as well as the communication bandwidth and quality required to support these LLT systems. Once these are determined, it is necessary to conduct performance testing for each of the example task areas in analog target environments.

6.2.1 Geological Tools and LLT

Terrestrial field geologists use a wide variety of tools to support their field studies. Some of the more common tools are navigation aids, rock hammers, hand lenses, and field books. As we move to other planetary surfaces, however, the local environmental conditions (e.g., temperature, pressure, gravity, etc.) require adaptation of these terrestrial-appropriate tools for surface operations via LLT.

In a recent Desert Research and Technology Studies (RATS) field test, an astronaut/engineer and a field geologist tested and evaluated various geological tools (Figure 6.1) that could potentially be used by astronauts on future surface missions (Young et al., 2013). Their goal for the field test was to evaluate the effectiveness of a set of terrestrial geologist's tools used by crews during EV activities and to establish the protocols and technology needed for an eventual manned mission to an asteroid, the Moon, or Mars.

Figure 6.1: Astronaut testing the tool caddy from the 2009 Desert RATS field test (Image: NASA/JSC).

Tools and instruments used by the geologist/astronaut in a spacesuit on a planetary surface will be different than the tools used by a robotic asset on that same surface. The efforts of the 2010 Desert RATS team in developing mission flight rules, protocols, and tools yielded vast quantities of data on how existing technologies need to be adapted to fit the needs of eventual crewed/robotic planetary surface missions. In the same way, tools must be adapted and tested for use by astronauts working through LLT.

6.2.2 Supporting Distant Exploration Missions by Using Local Resources

As human space exploration travels farther from Earth, astronauts will become more dependent on locally accessible resources, ISRU. There are a number of activities required for conducting ISRU for gases, liquids, and solid materials. These activities include: prospecting, mining, transporting, processing/purifying, fabricating, storing of gases and liquids, and assembling of structures. Design and engineering of the robotic assets to conduct these activities at each target destination defines a range of technical requirements to be addressed.

6.2.3 Communications Systems

A critical element of LLT for planetary exploration is having a robust communications system between the operators and the deployed robotic assets. The availability and reliability of communications channels with sufficiently high data bandwidth and low latency will determine the degree to which LLT will be effective. Given that missions to various destinations may have different requirements, in this section, we provide general communications requirements, based on previous and current experience (Figure 6.2).

Often, teleoperation is phrased in terms of an astronaut in a habitat (Controller) and a robotic surface rover (Asset). Various planetary exploration scenarios are envisioned, e.g., an astronaut on an orbiting platform or in a surface habitat controlling an exploration rover on the surface; or an astronaut in an orbiting platform engaged in remote habitat construction.

Four essential elements of the Control–Asset communications channel are that it must be of sufficient duration, data rate, robustness, and low latency.

Duration

Landed habitats or those in stationary orbits have continuous communications with all robotic assets in range. When habitats or communication satellites are orbiting non-synchronously, then the duration of communication windows must be addressed.

The durations of the tasks envisioned for LLT are typically on the timescale of an hour or more. One obvious requirement, therefore, is that the Controller must be in continuous communication with an Asset for this duration. However, this requirement could impose lower-level requirements on the Controller or the Asset. For instance, for an orbit–surface scenario, the Controller would have to be in a sufficiently high orbit to be in continuous

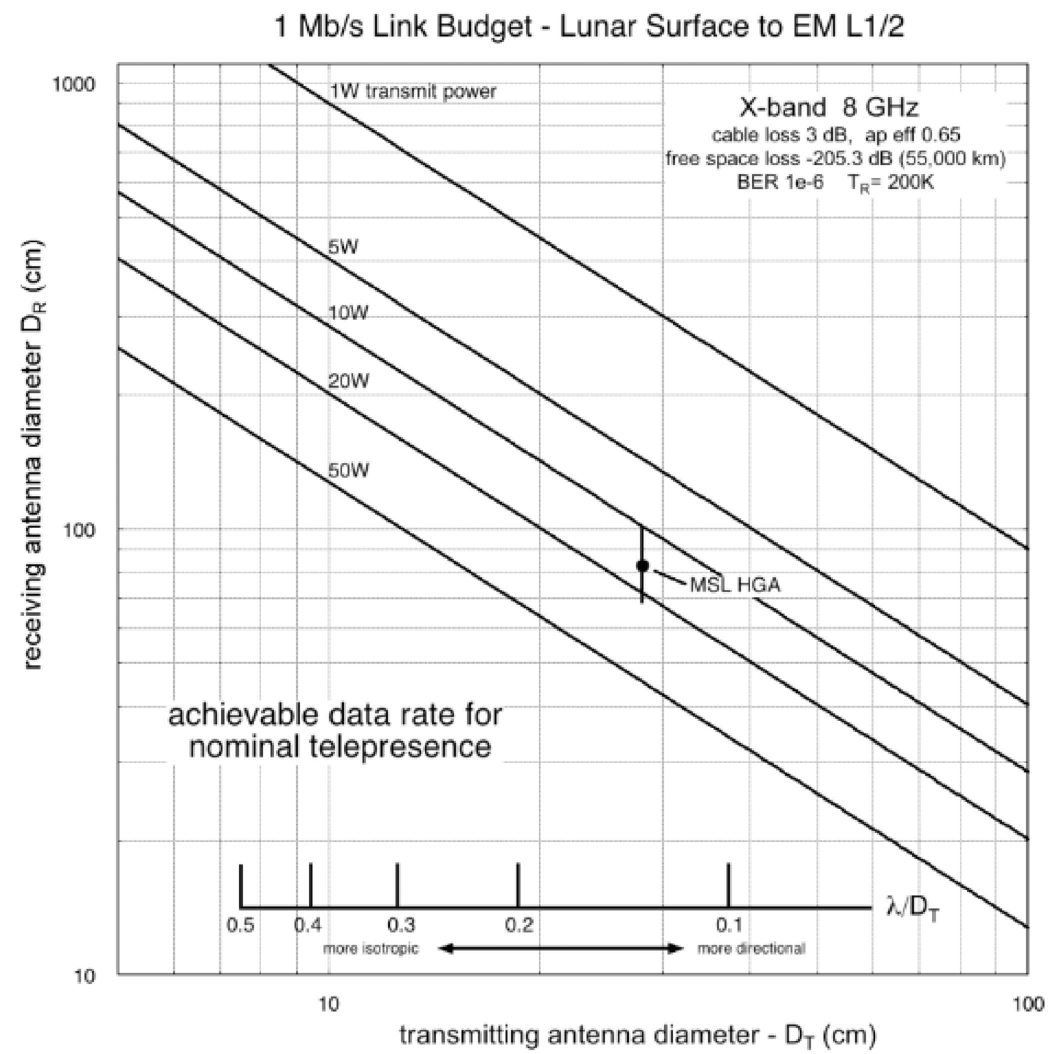


Figure 6.2: Link budget based on a notional bandwidth of 1–3 Mbps (ISECG Technology Working Group, 2018; Lester, 2014) over a distance of 60,000 km (lunar surface to an Earth–Moon Lagrange point). Assuming X-band communication, this quantifies the architectural constraints. Assuming a MSL-type 25-W transmitter with a ~30cm pointed high-gain antenna (HGA), efficient connection can be achieved with a 1-m pointed antenna at the EM Lagrange point habitat. The surface HGA will have a beamsize of about 10°, which determines how accurately it must stay pointed at the habitat overhead. This defines one point in the trade space.

communications. For reference, at Mars, many of the current Mars orbiters have relatively low orbits, such that they can communicate with a lander for only several minutes. By contrast, the outer moon Deimos orbits slightly above areostationary altitude and may be used to provide long duration communications.

Data Rate

To conduct LLT, an acceptable data rate must be maintained, with a commonly adopted threshold being 1–3 Mbps (ISECG Technology Working Group, 2018; Lester, 2014). Maintaining this data rate, with an adequate signal-to-noise ratio (see "Robustness" below), is determined by the telecommunications system between a Controller's habitat and an Asset, together with the distance between them.

Robustness

Telecommunications protocols involve signal-to-noise ratios and error correction codings. Coding and decoding the data requires additional processing power for low error rates which can increase latencies. Unanticipated communication interruptions must be accommodated in a fail safe manner. However, for LLT, some of these requirements of telecommunications quality may be reduced. For instance, for a scenario involving real time navigation of a rover across a surface, having video with some amount of noise in it may be acceptable.

Sensors: Immersive Multi-Sensory High-Fidelity Telepresence

A fundamental requirement for effective LLT is that the deployed sensing capability must support perception of the surroundings and conditions to remotely accomplish assigned tasks. This allows a teleoperator to feel immersed in the environment through the deployed robotic systems. An immersive telepresence experience relies on multi-modal sensor data (Podnar, 2019a).

For effective situation awareness, high-fidelity sensory cues are required, including geometrically correct wide-angle binocular stereoscopic vision, binaural stereophonic audition, haptic feedback, kinesthetic proprioception (i.e., the sense of the relative positions of neighboring parts of the body), and vestibular spatial orientation. It is critical to provide as rich a sensory experience as is practical to allow the remote operator an immersive sense of being present. Together with force-reflecting extremities and vestibular spatial orientation to provide significant physical cues of the environment, immersive visual and aural sensory cues are fundamental to situation awareness.

In a geometrically correct telepresence viewing system, it is insufficient to consider only the camera. To reproduce reality as if the viewer were directly gazing on a scene, the display system must also adhere to equivalent geometries. When camera imagery is displayed on a screen, it is natural to consider this monitor as a window "through" which the viewer gazes. By strictly adhering to equivalent geometries of a scene through a window, each object in view can be accurately represented.

The ability to modify the effective scale of a real scene without violating these geometric constraints is a powerful augmentation of the perceptual capabilities of the human Operator. Modifying the effective scale of the stereoscopic camera system does not involve changing the magnification of the cameras (zooming), as this introduces depth distortions along the optical axis. It is purely by changing the interpupillary distance of the camera lenses that a scaled viewing geometry is achieved. One example is deployment of a scaled stereoscopic camera on a manipulator that increases the apparent scale of the viewed scene (Figure 6.3). This scale increase can be a few hundred percent for fine manipulation, or even greater for in-situ microscopic visual analysis. On the other hand, the scale of a real scene can be reduced, such as when surveying the terrain from a stereoscopic mast camera to aid in long-range navigation.

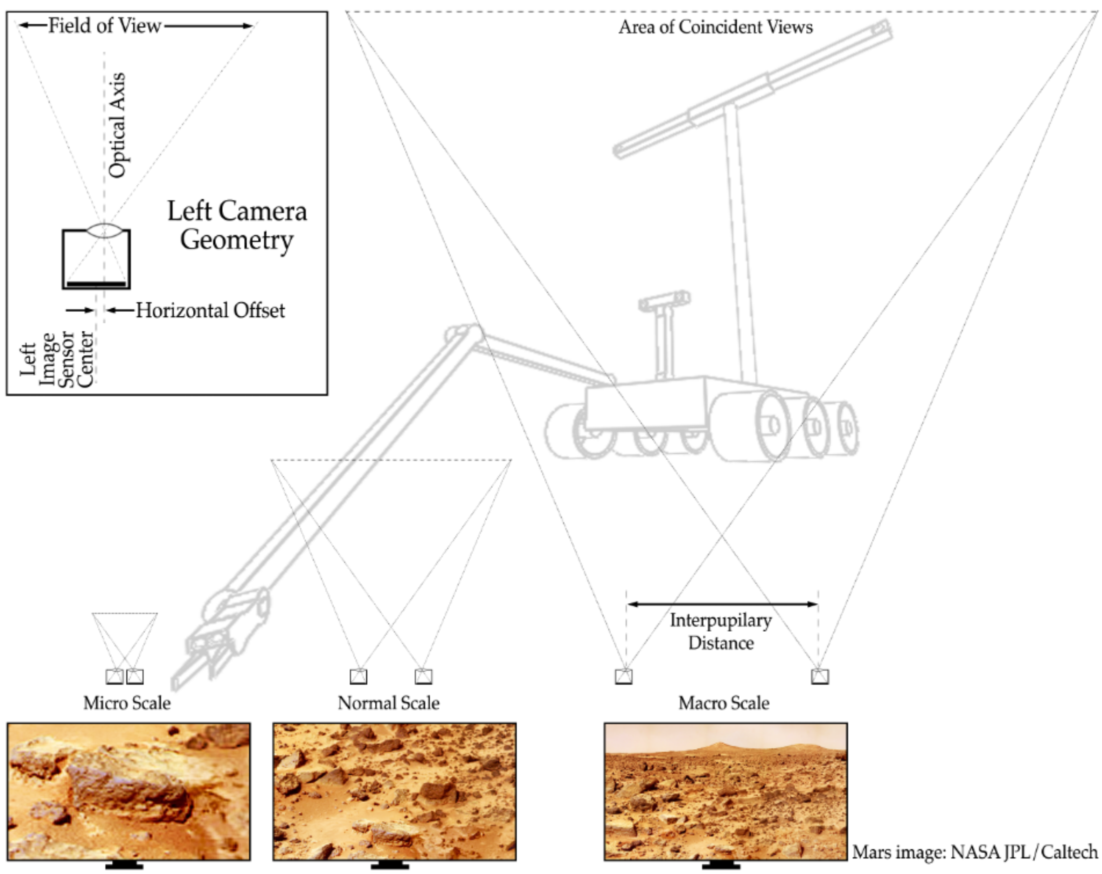


Figure 6.3: Stereoscopic cameras at three different scales (Podnar, 2019b).

Stereophonic audition (hearing) allows many subtle depth and manipulation cues that are processed subconsciously by an Operator. The hardware, power, and bandwidth costs of adding this sensory modality are relatively very small, yet the situation awareness it provides of the telepresently perceived environment can be invaluable. In environments where sound propagates naturally through a medium, audition can be employed as an effective immersive modality. When natural audition is not possible (i.e., in vacuum), audition can still provide very useful cues. Deploying contact microphones on the robot's structure can provide such cues for both mechanical system operation, and physical interactions between manipulators and the surface.

In addition to the high-fidelity force-feedback haptics discussed in Section 6.3.2, when the operator resides in a gravity field, the attitude (orientation) of the robotic vehicle or end-effector can be relayed to the Operator for vestibular spatial orientation and reproduced by adjusting the attitude of the Operator's chair at relatively low frequencies. An inertial measurement unit on the deployed robotic system relays acceleration and orientation data to three actuators that drive the Operator's support platform. These inputs can be limited for safety to prevent jarring or over tipping the Operator. In any case, relatively higher frequency sensations (e.g., collision and vibration) can provide richer "seat-of-the-pants" proprioception.

The systems that remotely sense these multiplicities of cues and reproduce them to the Operator must be developed and refined for operations for each target exploration site. Training in using these systems effectively will take place on Earth before departure, while en route, and while approaching the exploration destination. Productive work will be accomplished through the pre landed robotic assets with increasing efficiency as the communication latency diminishes during approach. Additional work will be accomplished following departure for Earth return.

6.3 Science Operations Challenges

There is a significant body of research that characterizes operator performance as affected by telepresence fidelity and latency. While a number of terrestrial use cases are summarized in Chapter 3 (above), the experiments that focus on the most critical performance requirements for LLT are fine manipulation and visual perception. In this section three research efforts are summarized, each of which investigate telesurgery, identifying the effects of latency and bandwidth on performance. The combined experimental results effectively identify the maximum communication latency and bandwidth baselines for fine manipulation in an LLT system. Experiments in fine manipulation and visual perception for exploration tasks such as geological field work are needed.

In this section, more detail is provided on LLT applications by:

- McMaster University's Centre for Minimal Access Surgery (CMAS)
- The U.S. Army Medical Research & Materiel Command's Telemedicine and Advanced Technology Research Center
- NASA's Extreme Environment Mission Operations (NEEMO)

6.3.1 McMaster University's Centre for Minimal Access Surgery (CMAS)

The world's first regular real telerobotic surgical service network was built and managed in 2002–2004, connecting the Centre for Minimal Access Surgery (CMAS), a McMaster University Centre (Hamilton, Ontario), and a community hospital in North Bay some 400 km away, using a Zeus robot (Haidegger et al., 2011). Surgery requires a high degree of precise dexterity and human awareness and is intolerant of both mistakes and long task completion time. As a consequence, the price of operational latency has been evaluated carefully for telesurgery. For example, the impact of latencies of up to about 500 ms has been established with some care for surgical telerobotics (Anvari et al., 2004; Perez et al., 2016). In these cases, on the basis of both task completion time and error rate, a latency of 500 ms has been determined to be basically nonfunctional for acceptable surgical performance. Factually, the concept of robot-assisted telesurgery came from NASA in the early 1970s and was then promoted by DARPA until the early 1990s (Takács et al., 2016).

6.3.2 The U.S. Army's Telemedicine and Advanced Technology Research Center

Early versions of Intuitive Surgical's da Vinci Surgical System used a proprietary short distance communication protocol through optic fiber to connect the operator and the remote surgical robot. The latest generations (da Vinci Si, Xi) facilitate further displacement of the two units. In 2005, The U.S. Army Medical Research & Materiel Command's Telemedicine and Advanced Technology Research Center (TATRC) presented collaborative telerobotic surgery on animals with modified da Vinci consoles able to overtake a master controller with a remote one through a public Internet connection (Flynn, 2005). During the experiment from Denver to Sunnyvale, the average round-trip latency was 500 ms, a delay which was disturbing for these physicians. Their evaluation confirms the CMAS studies above.

6.3.3 NASA's Extreme Environment Mission Operations (NEEMO)

NASA has conducted several experiments to examine the effect of latency on human performance in the case of telesurgery and telementoring. The NASA Extreme Environment Mission Operations (NEEMO) take place on NASA's permanent undersea laboratory, Aquarius, 19 meters below the surface in the Florida Keys National Marine Sanctuary. A special buoy provides connections for electricity, life support, and communications, and a shore-based control center supports the habitat and the crew.

The 7th NEEMO project took place in October 2004. The mission objectives included a series of simulated medical procedures with an Automated Endoscopic System for Optical Positioning (AESOP) robot, using teleoperation and telementoring (Thirsk et al., 2007). The AESOP was controlled from the CMAS (Ontario, Canada) 2,500 km away. A Multi-protocol Label Switching (MPLS) virtual private network (VPN) was established, with a minimum bandwidth of 5 Mbps. The signal delay was tuned between 100 ms and 2 s to observe the effects of latency. High latency resulted in extreme degradation of performance: a single knot tying took 10 minutes to accomplish (Doarn et al., 2009).

During the 9th NEEMO in April 2006 the crew used an M7 robot to perform real time abdominal surgery on a patient simulator. Throughout the procedure a microwave satellite connection was used. Each of the four astronauts had to train at least 2 hours with the wheeled in-vivo robots designed at the University of Nebraska. Latency was set up to 750 ms in these experiments. The effects of fatigue and different stressors on the human crew's performance in extreme environments were also measured.

The 12th NEEMO project ran in May 2007, and one of its primary goals was to measure the feasibility of telesurgery with the Raven and the M7 robots. NASA sent a flight surgeon, two astronauts, and a physician into the undersea habitat. Sewing operations were performed on a phantom in simulated zero gravity environment to measure the capabilities of surgeons controlling the robots from Seattle. This time, the Aquarius was connected to the mainland through a Spectra 5.4 GHz Wireless Bridge, allowing for a minimum of 30 Mbps bandwidth, and average latency of 70 ms. The HaiVision coder-decoder (codec) was used for video compression giving very good quality, but also introduced significant latency, up to 1 s. A group of three professionals guided the robot using commercial Internet connection, and the communication lag time was increased up to 1 s. Several simple tasks were performed as part of the Fundamentals of Laparoscopic Surgery (FLS) education module. The M7 demonstrated the first image-guided autonomous surgery (using a portable ultrasound system), and was able to insert the needle into a tissue phantom by itself.

These experiments establish communication latency and bandwidth baselines for LLT and inform the design of communications systems for planetary LLT exploration. Experiments in fine manipulation and visual perception for exploration tasks such as geological field work are appropriate next steps to validate communication latency and bandwidth requirements for planetary exploration.

6.4 Technical Limitations

6.4.1 Communication Latencies

We define "real time" human presence as human sensation, dexterity, and mobility, on the order of the human reaction times, from touch at 150 ms to vision at 250 ms. For effective LLT field science tasks, the required two-way communication latency, due to the speed of light, can only be achieved within distances of about 23,000 km. To put this in perspective, Earth geostationary orbit is half again that at 35,768 km, and the Moon is more than 10 times this distance. The enormous distances between the Earth and Mars result in two-way communication latencies from six to over forty minutes, depending on the relative locations of the planets. Therefore, performing the most demanding LLT science tasks from Earth is not practical any farther than geostationary orbit.

To achieve real time human presence and control, human beings must ideally be positioned within 23,000 km (and closer when electronic communication delays are added). For Mars, areostationary orbit is well within this limit at about 17,000 km height above the Martian surface, whereas Phobos has a mean orbit radius of 9400 km and Deimos has a mean orbit radius of 23,500 km. Placing the human spacecraft within areostationary orbit or emplacing habitat outposts on Phobos can address the communication latency challenge. Deimos may also be considered in a mission plan.

6.4.2 The Performance Impact of Latency on Dexterous Manipulation

The premise of LLT is that putting humans close to the exploration site decreases command latency. In many respects, higher latency is mitigated merely by proceeding more deliberately. This drops the task into a "move-and-wait" operational cognitive realm.

Using the formulation for task completion time in Hannaford et al. (1994), Equation 2:

$$CT = N(t_0 + T) \tag{6.1}$$

where N is the number of moves required to complete the task, T is the latency, and t_0 is the "elemental movement time", which is the cognitive reaction time plus thinking time and physical reaction time. In the absence of latency, that collapses to $CT_0 = Nt_0$. So, the "price of latency" is the factor

$$CT/CT_0 = N(t_0 + T)/Nt_0 \tag{6.2}$$

which, for $t_0 \ll T$ is T/t_0. This is not quite as "elemental" as the cognitive reaction time. So, if one could think and move instantaneously, the cost might be 150 ms, which is the cognitive reaction time, but is probably more like 500 ms.That being the case, the price of latency for round-trip, Earth–Moon telerobotic control is more like $T/t_0 = 2.6/0.5 = 5.2$. That is, for cognitively intensive operations on the Moon, it will take about five times as long to do them telerobotically from the Earth than in situ. For Mars, the ratio is vastly higher.

The delay obviously depends on the complexity of the task. This has been mapped out for peg-in-hole tasks, with latencies up to a few seconds, by Hannaford et al. (1994) and Kim et al. (1992), and earlier by Sheridan and Ferrell (1963). How task difficulty and latency contribute to error rate and task completion time was considered by MacKenzie and Ware

(1993). The impact of latencies (of up to about 500 ms) has been established with some precision for surgical telerobotics (see Section 6.3).

Latency also imposes serious limits on haptic and tactile feedback. Even small delays seriously effect coherency in manipulation tasks. Rank et al. (2010) and Jay et al. (2007), find that latencies of about 100 ms can be troublesome in haptic-enabled telepresence systems. While teleoperation can be achieved with large latencies for some tasks, with concomitant large task completion times, even small latencies can completely compromise tasks requiring haptic and tactile feedback response.

It has also been observed (e.g., Hambuchen et al., 2006) that telerobotic grasping, with lack of haptic feedback, is done using more force when there is command latency. Integrating the applied force over the duration of grasp, which naturally increases with latency, can be interpreted as "wear-and-tear" on the dexterity target. Lower latency telerobotic control is therefore better suited for equipment survival and for safety with delicate manipulation targets.

7. Strategies for Addressing Challenges

The previous chapter identifies scientific and technological challenges to be addressed for effective implementation of LLT. This chapter identifies areas of systems development.

7.1 Developing New Exploration Systems

NASA has conducted real time LLT experiments from the International Space Station (ISS) to a rover on Earth. NASA is also working on new technologies that will utilize materials found on the Moon to produce oxygen, propellant, and construction materials. As previously mentioned, ISRU will be essential to both the success of lunar exploration and long-term human presence on the Moon. Prior to performing extraction processes on the Moon, it is necessary to prospect for rich deposits of these resources (Dolan et al., 2005).

7.1.1 International Space Station real time Command of Robots

In 2012, scientists and engineers at NASA Ames Research Center successfully conducted "surface telerobotics" test sessions from the International Space Station (ISS). The Surface Telerobotics series of tests represents the first fully interactive LLT remote operation of a planetary exploration rover by an astronaut in space. The primary objective of the testing was to collect engineering data to characterize system operation. This includes collecting data about how the astronaut works through the robot user interface, rover telemetry, and data communications.

During ISS Expedition 36, Astronaut Luca Parmitano remotely operated a K10 planetary rover in the NASA Ames outdoor testbed from the ISS. Parmitano used the K10 to deploy and inspect a simulated, Kapton-film-based radio antenna (Figure 7.1).

Figure 7.1: A K10 rover can be controlled by an astronaut onboard the International Space Station for LLT experiments (Image: NASA Ames).

This test was intended to prove that humans can execute complex tasks remotely through LLT, such as setting up engineering structures on distant celestial surfaces from orbit. Its successful completion provided the first real time LLT data on orbit-to-surface human-robot interactions for future planetary missions. More tests like these are needed to prove new technologies and concepts of operation for LLT.

7.1.2 Lunar Microrovers for LLT Exploration and Prospecting

Another NASA/JPL program focused on lunar exploration using multiple, very small mobile robots such as the Pop-Up Flat Folding Exploration Rovers (PUFFER; Figure 7.2).

Conventional NASA robotic missions deploy few, relatively large, very capable rovers equipped with precision analytical instruments (i.e., MER, MSL, Mars 2020; see Section 4.2). Augmenting large robots with many microrovers widely dispersed at multiple exploration sites, controlled through LLT with a customized set of instruments, supports a wider, more comprehensive geologic reconnaissance of ISRU target resources (Spudis and Taylor, 1992).

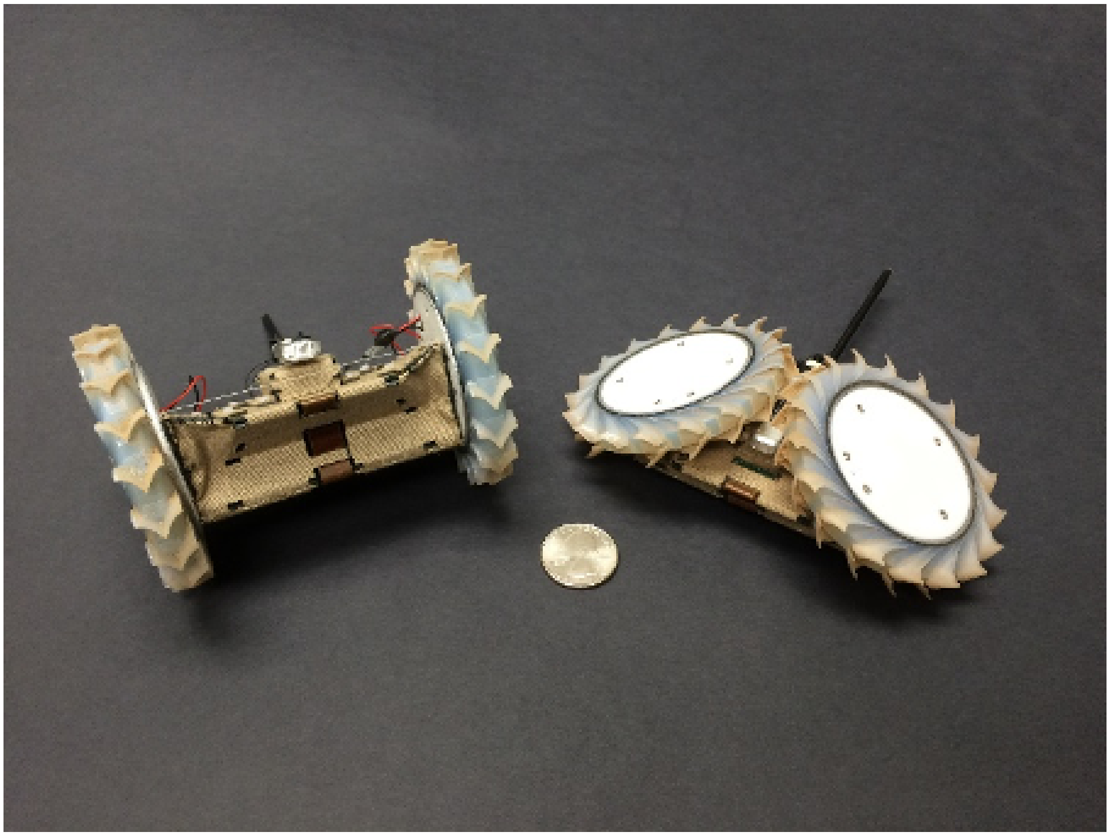


Figure 7.2: PUFFER rovers are very small, fold-up rovers based on origami. Multiple PUFFER rovers can be stacked and delivered as a single package to the lunar surface (Image: JPL/Caltech/NASA).

While flagship rover missions that investigate particular localities to answer specific science questions will still be deployed, a cross-referenceable set of measurements taken at a great number of localities on the Moon will provide a greater data return for both ISRU operators as well as lunar geologists. Controlling multiple assets from orbit via LLT validates this exploration approach for use on other more distant destinations.

7.1.3 Identifying New Terrestrial Field Sites for Testing LLT

Field trials using progressively more realistic prototypes of planetary rovers and their scientific instruments have successfully been utilized beginning with the Mars Pathfinder mission. Several of the more tested field sites include the Mojave Desert, Death Valley, Rio Tinto, Svalbard, and the Atacama, to name a few (Arvidson, 2011; Bonaccorsi et al., 2011; Cabrol and Wettergreen, 2011; Davila and McKay, 2011; Fernandez-Remolar, 2011; Hauber et al., 2011).

Experience has shown that terrestrial analog field experiments help to train the science teams to conduct field work and in-situ observations remotely and pave the way for the transition into operations for planetary surfaces. Similar terrestrial analogs for target destinations will need to be identified and experiments supported there to validate LLT.

7.2 Operational Task Planning and Scheduling for LLT

Planning and coordination for a system that includes astronauts local to the exploration site, deployed robotic assets, and terrestrial scientists and engineers in a proverbial "backroom" requires various levels of planning and scheduling tasks to be conducted. The examples provided here are from research conducted for NASA (Elfes et al., 2006).

Whereas terrestrial scientists will typically define the highest level mission goals, a human LLT "telesupervisor" local to the exploration site must monitor and control the immediate mission execution. This telesupervisor monitors the progress of the assigned autonomous robotic tasks in real time and teleoperates any robot vehicle or its subsystems when needed by LLT. The system architecture ideally supports a multi-level autonomy spectrum as defined in (Heger et al., 2005).

7.2.1 Robot Supervision Architecture

Task Planning and Monitoring and Robot Fleet Coordination are key roles that lie at the core of a Robot Supervision Architecture, an example of which is depicted in Figure 7.3. The mission plans (which may be created and edited with the assistance of software planning tools) are then assigned to a Robot Fleet Coordination module, within which further decomposition into subtasks is conducted, and then assignment of these subtasks is communicated to the individual robot controllers.

Robot Fleet Coordination also collects operational results from all robots and integrates them for convenient human monitoring and analysis. The Monitoring Level also includes Perception–Decision-Making–Actuation sequences to monitor multi-robot operations at the system level, and to analyze for high-level hazard and assistance detection. Robot Fleet Coordination imagery and telemetry are combined for building regional imagery and maps, and are also presented graphically to the telesupervisor.

Robot Telemonitoring allows each robot to be constantly monitored at low bandwidth by the human telesupervisor with imagery and data updated regularly from each deployed robot vehicle. This can include periodic images from the robot's cameras, status data such as battery charge, vehicle attitude, motor temperatures, and other telemetry.

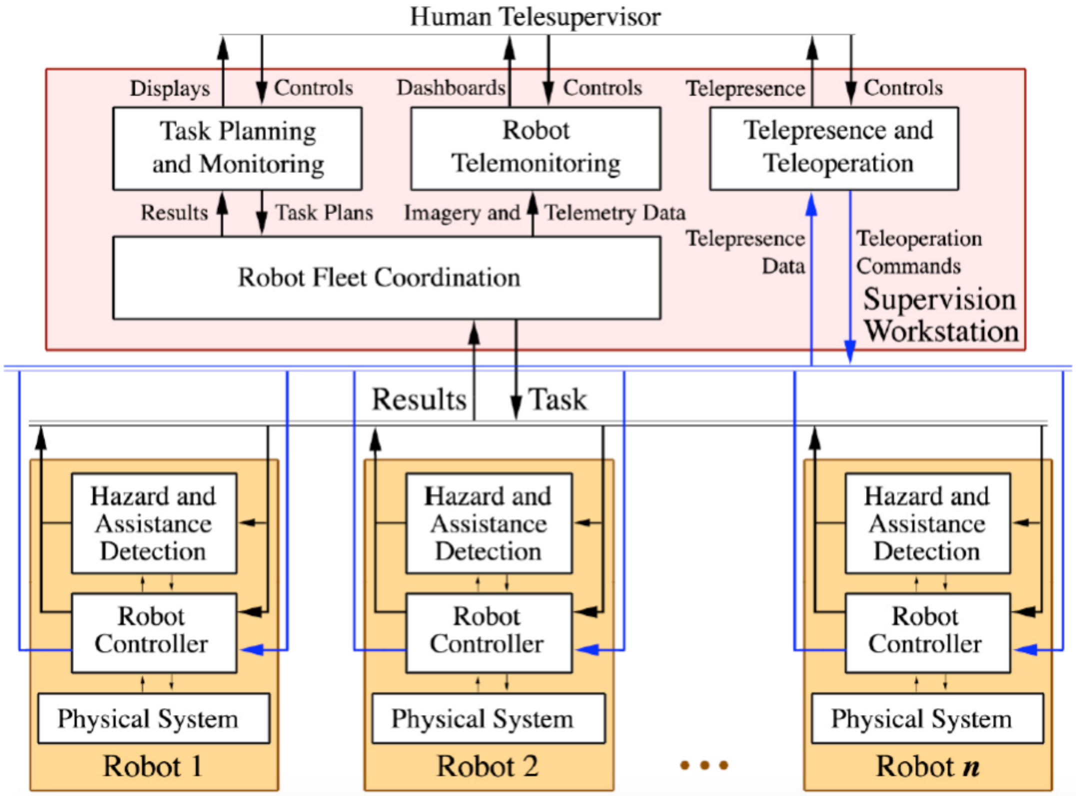


Figure 7.3: Example of a Robot Supervision Architecture (Diagram: G. Podnar)

7.2.2 Robot Subsystems

A Robot Controller subsystem in each robotic asset receives a collection of tasks from Robot Fleet Coordination. The robot controller has direct access to all of the robot's subsystems to drive actuators and read sensor data. When a robot involves a relatively complex combination of mobility, manipulation, and other engineering or science subsystems, the corresponding robot controller may be implemented as a collection of modules responsible for each subsystem.

Every robotic asset includes a Hazard and Assistance Detection (HAD) subsystem that is responsible for the robot's and the mission's integrity, including vehicle monitoring and health assessment and failure detection, identification, and recovery. It assesses the robot's sensor data to infer potential hazards or the machine's inability to complete a task, and communicates with the Robot Fleet Coordination module at the Supervision Workstation, which can then inform the telesupervisor to take the appropriate action(s).

The major motivation for developing the HAD algorithm is to be able to identify, alert, and prioritize requests for the telesupervisor's attention. It also optimizes and recommends a particular order to the operator for fixing multiple rovers efficiently. The goal the algorithm focuses on is to minimize overall robot pause-time—to get the least number and shortest overall duration of inoperative rovers—without neglecting any long enough to endanger them. These alerts are sorted and prominently listed for the telesupervisor in the Assistance Queue on the workstation.

7.2.3 Robot Fleet Coordination: Prioritized Assistance Queue

For optimize performance of a system of multiple robotic assets, prioritizing the requests from the robots for assistance is necessary. Ideally, a priority queue recommends an efficient order of requests. The primary goal of the prioritizing algorithm is to minimize overall robot pause-time—to get the least number and shortest overall duration of inoperative rovers—without neglecting any long enough to endanger them. This includes assigning request urgency levels based on estimated time to address each hazard, and acceptable neglect times both for robot health and safety, and overall mission completion times.

7.2.4 Exceptional Conditions

When a mission needs additional scientific input from field experts on Earth (whether initiated by the LLT telesupervisor, or the Earth-based scientists), a delay for both the communications and the analysis must be added for each occurrence. In a similar way, when engineering consultation is required to address a robot physical system issue, support from the Earth-based engineering staff is essential. Mission planning and scheduling must also be designed to take into account these exceptions. Deploying LLT robots with high-fidelity telepresence and telemanipulation capabilities for immersive human operation is a preferred substitute to sending an astronaut to the exploration site to conduct an EVA as a last resort.

7.3 Orbital Deployment Decisions

For any specified off-Earth destination, similar cost, schedule, exploration productivity, and safety benefits arise from LLT regardless of whether humans explore from orbit or in situ. The primary focus in this section is with humans exploring an off-Earth destination from proximal orbiting habitats rather than from in situ habitats located on or below that destination's surface.

The most fundamental orbit attribute with respect to LLT is adequate proximity to the destination under exploration. Proximity is a necessary condition for low latency to enable productive LLT, but it may not be sufficient. Latency is dependent on many attributes of a communication interface between orbiting humans and robotic surrogates. In addition to the distance spanned by this interface, communications infrastructure scheduling may greatly affect latency. This scheduling might be required to resolve conflicts with other users or to cope with line-of-sight disruptions arising from orbit motion, surface rotation dynamics, and destination terrain.

7.3.1 Mars Orbital Selection

Acceptable latency for telepresence depends to some degree on the exploration task being conducted. Consensus among this study's participants finds 200 ms latency is sufficiently low to facilitate any envisioned exploration task. Assuming no appreciable latency contributions other than from round-trip light time at 300,000 km/s, putting humans closer than 30,000 km to their robotic surrogates will reduce light-time latencies to 200 ms or less. The moons Phobos (at a mean orbit radius of 9400 km) and Deimos (at a mean orbit radius of 23,500 km) lie well within the proximity constraint for Mars surface exploration, assuming line-of-sight communications links without "bent pipe" relays. Both moons of Mars have near-equatorial orbit inclinations. Consequently, a habitat near the orbit of Deimos is able to establish line-of-sight communications with surface surrogates nearer the poles of Mars than could a habitat orbiting near Phobos at a much lower altitude.

Particularly during high-dexterity or otherwise critical LLT operations, uninterrupted communications between orbiting humans and their robotic surrogates is essential. An orbiting communications relay constellation is typically unable to avoid interruptions because individual satellite elements cannot indefinitely maintain simultaneous lines-of-sight between humans and their surrogates. These interruptions occur for about a minute (e.g., TDRSS) when one constellation element hands over to another. Minimizing LLT communications interruptions is best achieved by maintaining the longest possible intervals with human/surrogate line-of-sight. Orbits implementing this strategy would therefore have periods nearly synchronous with axial rotation of the surface under exploration. In a Mars exploration context, an orbit near that of Deimos would offer nearly synchronous motion. At the Moon, periodic orbits proximal to Earth–Moon Lagrange 1/Lagrange 2 (EML1/L2) are roughly synchronous. Near small bodies with low gravity, station-keeping over a rotational pole may be practical to achieve continuous line-of-sight, even for mildly chaotic rotation.

Maintaining uninterrupted lines-of-sight to the Sun (for power) may be of critical importance to humans conducting LLT from orbit, regardless of the exploration destination. Except at times around a Martian equinox, orbits near that of Deimos have continuous lines-of-sight to both the Sun and Earth. If Earth communications or solar power infrastructure is emplaced near a rotational pole of Deimos, continuous communications or power generation is possible for over 5 months before and after local summer solstice. The remainder of a Martian year will enjoy nearly continuous communication or power generation from the other pole of Deimos. In contrast, an observer in orbit near Phobos will see the Sun and Earth occulted by Mars every 7.7 hours.

A phased approach to early Mars exploration focused on LLT from an initial Deimos habitat may progress as depicted in the following illustrations. Phase 1 could consist of LLT science activities being conducted from a radiation-protected buried habitat on Deimos (Figure 7.4). This could be followed by a Phase 2 that would include both continued science exploration from Deimos and construction of an initial Mars habitat and power infrastructure (Figure 7.5). Ultimately, once astronauts land on Mars, a more extensive in-depth science exploration would be conducted safely from a protected subsurface habitat as illustrated in Phase 3 (Figure 7.6).

7.3.2 Lunar Orbital Selection

In a lunar exploration context, the cislunar and translunar libration points (EML1 and EML2, respectively) lie about 60,000 km from the Moon. At 400 ms, the most latency-critical fine manipulation tasks would be impractical from the vicinity of EML1/L2, but less demanding operations (such as rover driving) might be possible. For humans near EML1/L2, solar occultations by the Earth and Moon can occur during eclipse seasons arising every 6 months. Occultations of Earth by the Moon near EML2 can be minimized in "halo" periodic orbits, but these communications interruptions don't occur in periodic orbits about EML1. As at Mars, frequency and duration of Sun/Earth occultations tend to increase as orbit distance from the Moon decreases.

Due to its high accessibility from Earth, the Moon stands apart from other off-Earth exploration destinations. Risk to humans is minimized in short-period equatorial lunar orbits because flight opportunities to and from Earth enjoy maximum flexibility. Following LEO departure on any specified day, nearly constant change-in-velocity magnitude (Δv) will deliver a payload to a low-risk-orbit habitat three to five days later. Likewise, departure from a low-risk-orbit habitat on any specified day will result in Earth return three to five days later after expending nearly constant Δv.

These low-risk orbits lie in planes near that of the Moon's equator, and they have selenographic periods shorter than about 2 days.[1]

Another consideration in the context of humans proximal to EML1/L2 is orbit stability. Periodic orbits about these libration points are inherently unstable, and Δv-efficient station-keeping requires small impulses typically be imparted on a weekly basis (Folta et al., 2011). This activity may conflict with productive LLT operations. In contrast, lunar distant retrograde orbits are inherently stable and are also low-risk orbits at lunar inclinations near 180° and radii from 3000 km to 16,000 km (Adamo et al., 2014).

Many of the LLT considerations discussed here are already under assessment to some extent in LEO aboard the ISS; specific LLT-pertinent ISS experiments are cited in Appendix B.

Lunar surface exploration from the Gateway cislunar orbit habitat under development by NASA will be an effective means for assessing orbiting LLT in a variety of scenarios. Initially, the Gateway will be placed in a highly elliptical EML2 halo orbit whose distance from the

[1] A circular lunar orbit with radius near 16,000 km has a selenographic period of 2 days. In contrast, typical periodic orbits about EML1/L2 have selenographic periods near 7–14 days.

Figure 7.4: Phase 1: Science Activities, LLT from Deimos: Initial scientific exploration of Mars can be conducted from a buried habitat on Deimos that protects the astronauts from radiation during their long duration presence in the Martian vicinity. For the astronauts' long-term health, a centrifugal habitat could provide artificial gravity. Wheeled and flying LLT robots deployed at widely dispersed science sites allow the astronauts to explore both safely and efficiently (Image: Keck Institute for Space Studies [KISS]).

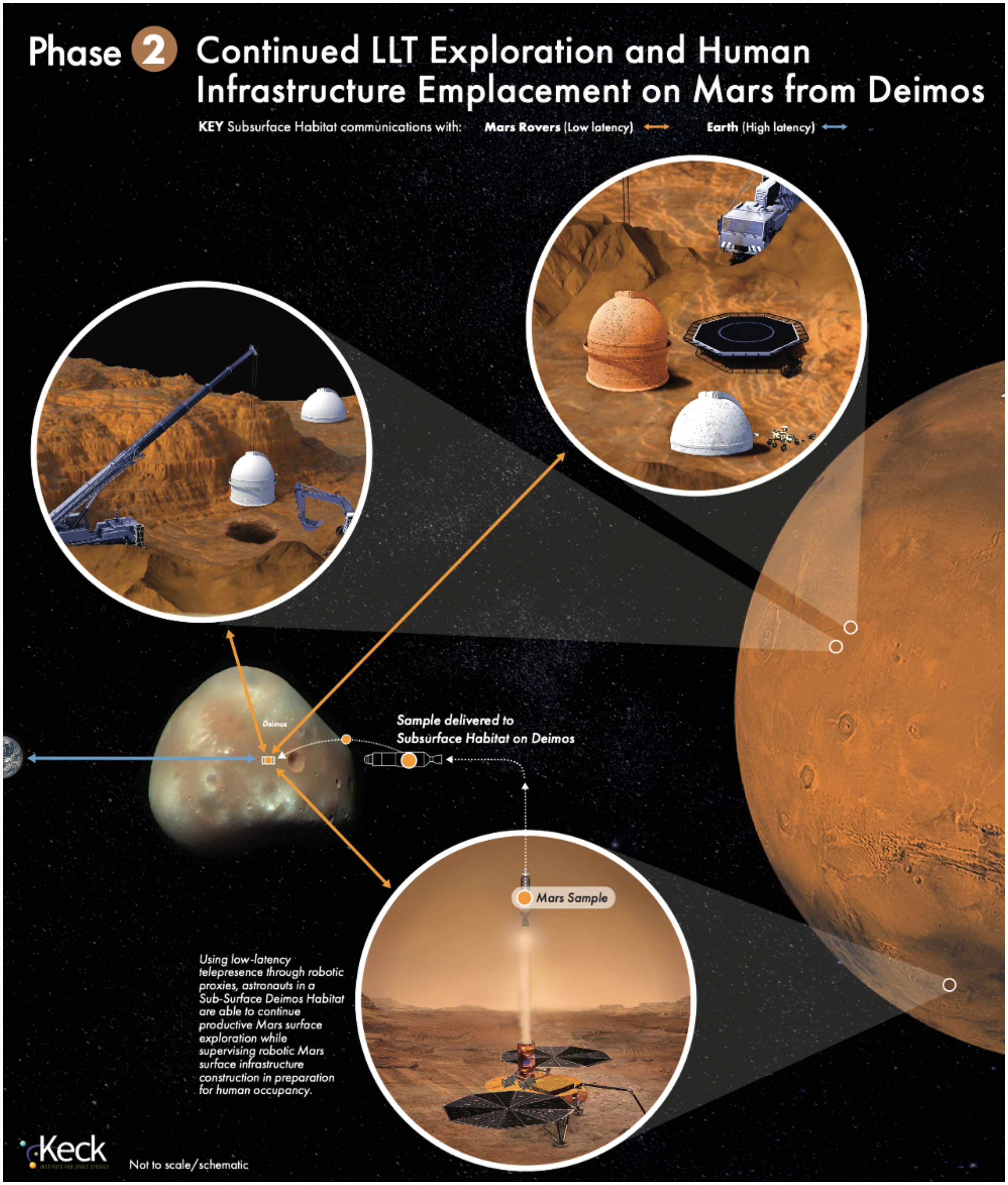


Figure 7.5: Phase 2: Mars sub-surface habitat and infrastructure construction, sample return, LLT from Deimos: While continuing LLT scientific exploration, astronauts working from Deimos can construct a subsurface habitat on Mars and a power generating facility for longer duration stays. Geologic samples from Mars can be delivered to the habitat on Deimos via small rockets for detailed scientific analysis (Image: Keck Institute for Space Studies [KISS]).

Figure 7.6: Phase 3: Habitat maintenance and continued LLT exploration from Mars sub-surface habitat: Once astronauts land on the surface and inhabit their protected Martian base, more extensive scientific explorations can be conducted via LLT through robotic assets deployed at distant and challenging sites. Ongoing maintenance of local infrastructure can also be accomplished safely using LLT (Image: Keck Institute for Space Studies [KISS]).

Moon will vary from 70,000 km to 1500 km. These distance variations will permit a variety of light-times to be evaluated over the halo orbit's 6-day period, most of it spent at distances beyond 30,000 km. While at greater lunar distances, the Gateway will support continuous line-of-sight communications with an entire region on the Moon's surface for days at a time. In addition to correcting the halo orbit to safely remain in cislunar space, the Gateway's Propulsion and Power Element has capability to substantially modify that orbit. This capability could lead to entirely different lunar exploration trade spaces, such as those evaluating highly accessible, low-risk orbits.

7.4 Designing Communication Strategies

High-fidelity telepresence depends on sufficient communication bandwidth between a robotic proxy and its human operator. Most of the bandwidth is required for imaging and must be achieved in the robot-to-habitat direction. Control bandwidth from human to robot is much less constraining. For a minimal level of human telepresence, enabling eyesight-like field of view, resolution, and assuming contemporary compression strategies, the communications system must provide a bandwidth on the order of 1–3 Mbps. Frame rates can be varied to some degree depending on the task. For example, lower frame rates may be adequate for simple traverses, while higher frame rates are necessary for dexterous manipulation. This bandwidth is needed over distances up to several tens of thousands of kilometers. Communications distance informs requirements such as transmitter power and frequency, together with the size and geometry of transmitting and receiving antennae. For example, with a notional 1-m-diameter HGA for the operator, the robot will need a 20-cm HGA to pump 1–3 Mbps (ISECG Technology Working Group, 2018; Lester, 2014) over a distance of 44,000 km at X-band (8 GHz) frequencies. This robot's HGA will have a beam width of about 10 degrees. The robot's antenna will need to be continuously pointed to some fraction of that angle in order to assure full communications bandwidth. These variables constitute a trade-space that can be adjusted to conform to engineering and operational requirements.

Orbital relay satellites can form one aspect of a communication network that allows wider area coverage between robots and operators. Even before relay satellites are operational, communications networks can be deployed by using multiple mobile robotic assets as local nodes. Specific fixed-emplacement relay assets may also be erected as part of a full communications network.

8. Roadmap to LLT-Augmented Exploration

LLT is an exploration technique that is relevant to all phases of the next generation of human exploration. Advancing from practical, proven terrestrial application today, NASA and its international partners have already conducted real world LLT engineering experiments from astronauts on the International Space Station through terrestrial robotic assets in an analogue environment (Jones, 2017).

LLT experiments will continue from the cislunar Gateway habitat as crews conduct productive planetary science and sample returns from the Moon. Beyond the Moon, LLT activities that prove valuable in cislunar space also feed-forward into the conduct of crewed near-Earth object exploration and planetary missions. Planning for these future exploration missions creates an incentive for further LLT refinement in cislunar space. It is critical to develop a comprehensive LLT architecture that starts with relatively near-term missions in the Earth–Moon system (cislunar space) that feed forward to enable a sustainable human presence in destinations such as the Mars system (Bobskill et al., 2015; Lester and Thronson, 2011; Lupisella et al., 2012; Lupisella and Bobskill, 2012; Olson et al., 2011).

8.1 Lunar Gateway

The next chapter of human space exploration continues to unfold, with NASA's current focus on a return to the Moon by 2024. NASA's initial steps are aimed at constructing a lunar orbital laboratory, or Gateway. The Gateway will consist of a habitat, airlock, utilization module, supply module, and a power and propulsion module (Figure 8.1). The mission goals are to establish astronauts in lunar orbit, host payloads to explore the Moon and its resources, and prepare technologies and techniques for lunar surface access and eventual Mars expeditions.

The Gateway will host LLT operations with astronauts controlling landed assets to explore the lunar surface (Burns et al., 2019; Crusan et al., 2019). Next, the Gateway will serve NASA and its partners as a site to assemble, test, and deploy precursor landers to the surface ahead of crewed landings (Cichan et al., 2018). Once astronauts are on the lunar surface, LLT will enable them to conduct wide-ranging lunar surface exploration from their safe surface or sub-surface habitats through robotic assets via real time communications.

Figure 8.1: Gateway will host LLT operations with astronauts controlling surface rovers (Image: NASA).

8.2 Lunar Surface Exploration and Exploitation

In addition to extensive lunar geological exploration campaigns, there are some exploration target sites of greatest interest. The deep, near-permanently shadowed craters of the Moon's polar regions may be preserving a reservoir of water ice. While the lack of sunlight, extreme cold, and steep, rocky slopes within such craters make human exploration prohibitively hazardous, NASA plans to deploy robot surrogates to map and sample these resources. LLT will enable astronauts to explore these hostile environs by proxy, first directing robot surrogates to identify and then sample polar water ice deposits.

Before astronauts land to inhabit a permanent lunar base, LLT will reduce the risks of building that base. Once humans establish themselves on the surface, they will continue scientific exploration, maintenance, and infrastructure expansion via LLT. Astronauts may also remotely monitor and maintain automated water extraction plants needed to produce propellant and water and oxygen for life support (see Section 8.4 for more extensive in-situ resource utilization plans).

In addition to the cost-benefits of employing LLT technology, cost is a programmatic factor suggesting that LLT evolution from crews who are first orbit-based and later surface-based is an advisable strategy. The mission cost proxy developed in Section 2.4 indicates that reaching the lunar surface is about twice as expensive as reaching low lunar orbit.

8.3 Near-Earth Object Exploration

Near-Earth objects (NEOs, which include near-Earth asteroids and comets) may be visited by human explorers as they move beyond the Moon and prepare for Mars expeditions. LLT offers a potential solution to the daunting environmental challenges NEOs pose to robots and astronauts: very low gravity, rough surface topography, and unstable "rubble pile" surfaces of loosely bound rocks and dust particles (Figure 8.2).

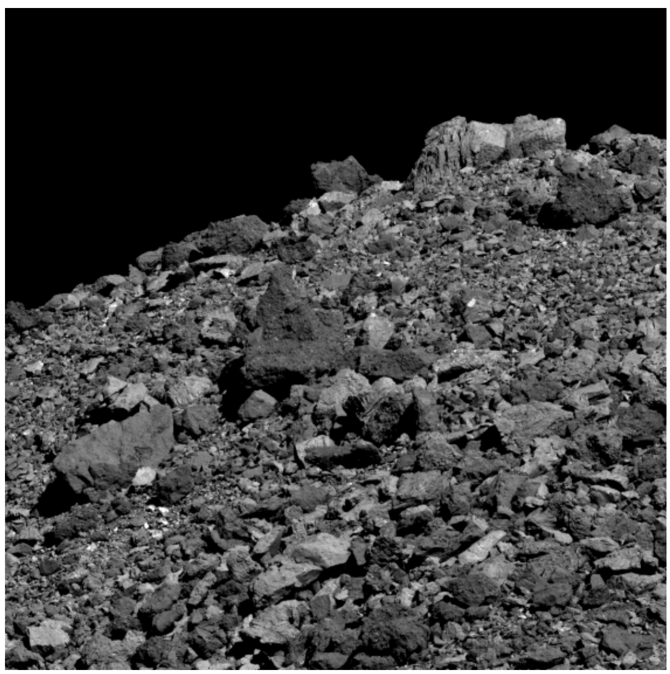


Figure 8.2: A boulder field on Bennu, a rubble-pile NEO, imaged in March 2019. (Image: NASA/University of Arizona)

Robotic craft controlled from Earth have successfully mapped small NEOs from orbit, but landers have struggled to cope with rough, low-gravity comet and asteroid surfaces because they had to land autonomously. For example, in 2014 Rosetta's Philae lander descended to the surface of comet 67P/Churyumov–Gerasimenko. After bouncing, the probe settled on its side in a deep crack under a shadowing cliff, relaying only limited scientific data (see

Section 4.2.5). In February 2019, the Hayabusa 2 probe's brief touchdown on asteroid Ryugu liberated a blizzard of rock shards that engulfed the craft as it ascended toward orbit. Mission controllers would not permit a suited astronaut to conduct field science in such a gritty, rough, hazard-filled environment.

A promising LLT exploration strategy will deploy small, manipulator-equipped spacecraft from a crewed vehicle orbiting above the NEO surface. Astronauts will teleoperate these robotic craft to explore the NEO surface thoroughly from their safe habitat. Astronaut-directed LLT will thus ideally move from early trials at the Lunar Gateway and surface to NEO expeditions, then to Mars orbit and its satellites, and finally to the Martian surface, and beyond.

8.4 Planetary Exploration and Other Moons

NASA's plans have long included launching a crewed expedition to the Mars system. Significant technological and biomedical obstacles challenge these plans. Because soft-landing massive payloads (20 metric tons or more; Drake, 2009) on the Martian surface calls for significant technology advancement, NASA's ability to place human explorers in orbit about Mars must mature well before the agency is able to commit astronauts to descent and landing. Calculations cited in Section 2.4 show that getting to the surface of Mars could easily be 3 to 4 times more expensive than getting to Mars orbit in the vicinity of Deimos, the outer moon of Mars.

Therefore, prior to landing humans, LLT offers an effective way for Mars-orbiting crews to engage in intensive and widespread surface activities through robotic sensors and manipulators carried on mobile robotic assets. Sample return is another mission goal that can also be conducted effectively at Mars via LLT, increasing science return through direct crew-scientist decision-making, thereby better selecting and returning higher value samples. While at Mars, the moons Phobos and Deimos may also be explored. Some specific operational and engineering considerations in evaluating LLT applications to Mars exploration are noted in Lupisella and Mueller (2016), and Lupisella et al. (2017).

As noted in Sections 8.1 and 8.2, orbit-based LLT operations that can then evolve into surface or subsurface-based LLT operations are envisioned for the Moon and the Lunar Gateway. A similar progression of efforts for other off-Earth exploration destinations is desirable.

Experience gained from and infrastructure developed for orbit-based LLT subsequently feeds forward when crews operate from a subsurface habitat. In this habitat, threats to the crew are dramatically reduced compared to EVA operations on the surface. Even if those operations are conducted in a pressurized rover, crew radiation exposure is virtually the same as in EVA garb and distance traversed from a subsurface habitat's safe haven is limited by the consumables carried. Consumables expended in cycling airlocks and high metabolic rates generated during surface activities are likewise minimized by LLT. Using LLT, the crew can stay on task longer without physical exhaustion or the need to replenish life-sustaining consumables, thus greatly increasing productivity with respect to comparable EVA operations. Under an LLT-dominated crew activity model, EVA will likely be confined to accessing crew transports, conducting brief ceremonies, and addressing unplanned contingencies.

These Mars scenarios identify a number of testing activities best conducted and proven in cislunar space: a) defining the telerobotic traverse range for landing site reconnaissance, preparation and sampling; b) telerobotic sample characterization and acquisition to better understand LLT science operations (e.g., difficulty, duration, and completion of tasks); c) orbital sample handling; and d) sample containment, including verification methods, time needed, and contamination control.

8.4.1 Planetary Protection of Mars

Astrobiology investigations face the risk of humans contaminating biologically interesting sites on Mars through organisms and compounds shed from astronauts, their EVA equipment, and their habitats. LLT can circumvent such risks by employing sterile rovers able to enter contamination-sensitive zones with minimal risk of compromise to any extant native life. Conversely, LLT isolates astronauts from physical contact with the surface, minimizing risk of back-contamination to Earth's biosphere. In the ultimate bio-protection mode, astronauts defer reaching the alien surface under exploration and use LLT from orbit to conduct all surface activity using robotic proxies.

Well-designed LLT systems will be capable of continued operation at higher latencies when astronauts are not proximal. This permits science activities and infrastructure development to proceed at virtually all times, albeit at reduced rates compared to operations in LLT mode.

8.5 Off-Earth Mining Resource Extraction and Use

Growing private and public sector interest in expanding current robotic and human activities in space is resulting in a need to find low-cost energy and resource supply solutions. The use and extraction of raw minerals and volatiles from the surface of the Moon, Mars, or near-Earth asteroids, is receiving renewed interest as a means to enable and sustain these development opportunities (Hempsell, 1998; Lewis, 1996; Martin, 1985; Sanders, 2018; Saydam, 2018). There are, however, still significant uncertainties in the feasibility of undertaking off-Earth resource extraction. It is envisioned that the Moon, being our closest celestial neighbor and host to several potentially valuable resources, may act as a proving ground for the development of resource extraction and utilization systems (Figure 8.3; Kornuta et al., 2019; Metzger et al., 2013).

The production of hydrogen and oxygen derived from water and made available to an in-space market has been identified as a critical near-term commodity (Kornuta et al., 2019;

Figure 8.3: Artist's rendition of a future lunar mining operation (Image: JAXA).

Lewis, 1996; Sanders, 2018). Some suggested uses for these products include propellant for spacecraft, contributions to life support systems in both orbiting space stations and surface research stations, and use in the manufacturing and processing of other lunar resources, i.e., metals and construction materials. Several lines of evidence, obtained from orbital observational data, point to enhanced hydrogen signatures within the permanently shadowed regions (PSR) of the lunar poles, which have been strongly linked to the presence of water ice (Feldman et al., 2001, 1998; Fisher et al., 2017; Gladstone et al., 2012; Lawrence et al., 2006; Li et al., 2018; Mitrofanov et al., 2010). Surface exploration missions will be necessary to investigate the nature of lunar polar hydrogen, confirm the presence of water, determine its spatial distribution and form, and evaluate the economic resource potential and technological feasibility of extracting lunar water (Colaprete et al., 2016; Sanders, 2018). Scientific surface missions can also assist in reducing the barriers to entry for commercial resource extraction activities growing the cislunar and in-space economy (Shishko et al., 2018).

The NASA FY2020 budget sets a priority to investigate the presence of lunar polar volatiles and to mature technologies for water resource extraction with the cited aim to conduct an integrated demonstration in the 2025 timeframe (NASA, 2020). Operating in the permanently shadowed regions of the Moon will be challenging due to the extremely cold temperature environment (as low as 40 K) which represents a potential hazard for human missions. The use of robotic systems provides a safer alternative and can be developed to locate, analyze, extract, process, transport and utilize lunar resources as well as construct and maintain surface infrastructure (Kornuta et al., 2019; Metzger et al., 2013).

None of these ISRU activities need to be conducted hands-on by astronauts as they can all be accomplished most effectively using LLT technologies. Proving these LLT systems at the

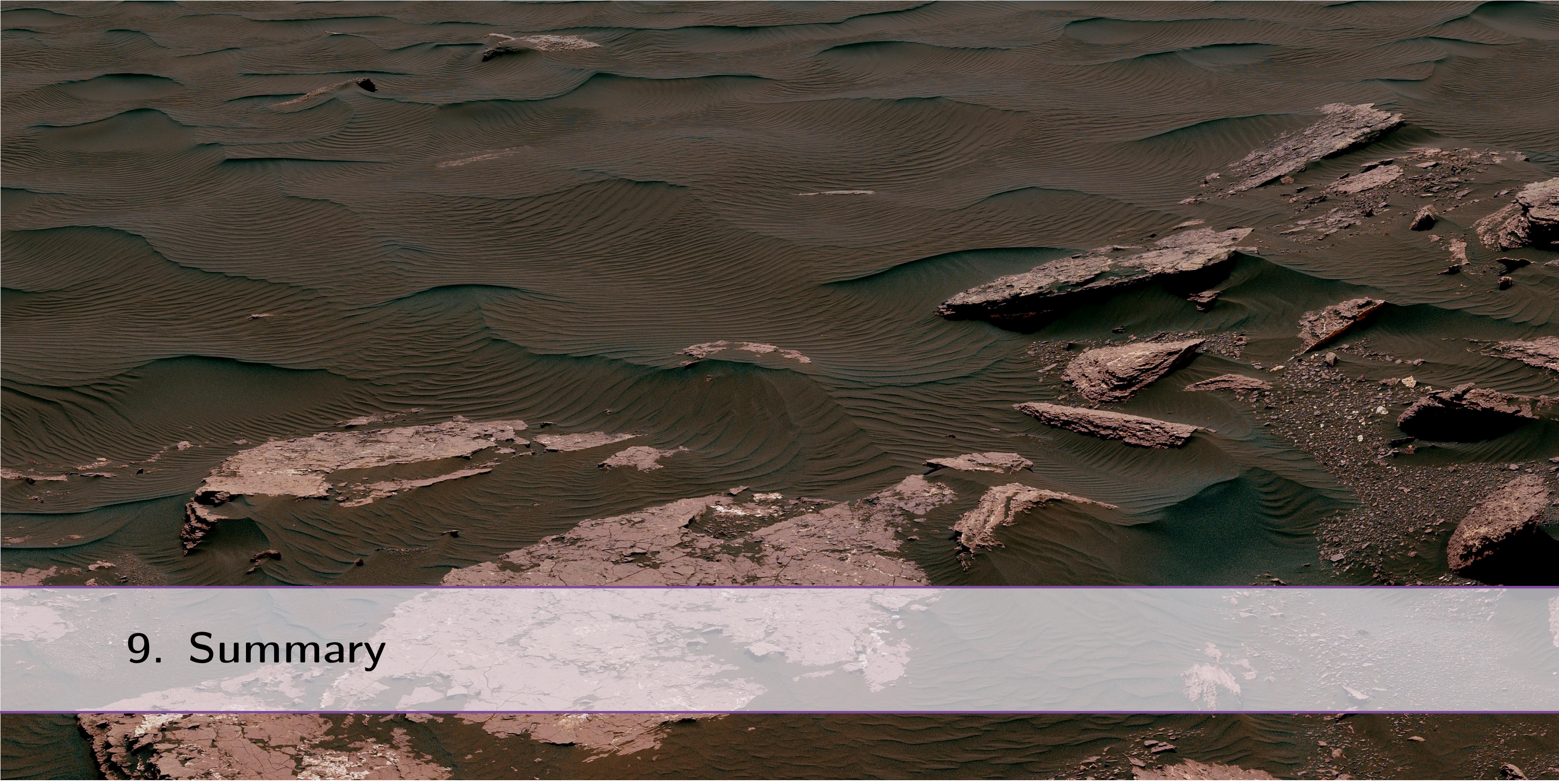
Moon will feed forward to resource extraction techniques on other celestial bodies (i.e., NEOs and Mars).

8.6 Programs for Research and Development of LLT Robotic Systems

Robotic systems are crucial for making solar system exploration, habitation, and ISRU tractable. Assessing current capabilities and planning the necessary research and development programs will lead to successful deployment, validation, and refinement of these systems. This report is the outcome of two workshops specifically organized to define these efforts comprehensively and rigorously with experts across the relevant disciplines working together.

While robotic systems can be sent vast distances to search for, extract, and transport resources throughout the solar system, the vision that these systems can be sent in advance of humans to prepare sites for human arrival must be tempered with a formal assessment of autonomous robotic systems and the level and immediacy of human intervention required for successful mission concepts (Section 6.1.3 Incorporating Autonomy into LLT Tasks).

On the other hand, the vision of sending human explorers to other solar system bodies requires maximizing their safety and effectiveness. Recognizing that robotic systems will augment the human capabilities requires that LLT systems be designed, proven, and optimized within a human-robot collaborative architecture.



9. Summary

In 2016 and 2017, the Keck Institute for Space Studies hosted two workshops titled "Space Science Opportunities Augmented by Exploration Telepresence." World-class representatives from telerobotics, planetary science, and human spaceflight gathered together to evaluate the benefits and challenges of pursuing a strategy for collaborative human and robotic planetary exploration. By exploiting the rapid progress in robotic telepresence technology, humans in habitats proximal to an exploration destination will, through robotic surrogates, achieve immersive presence at multiple exploration sites, including those considered too dangerous for astronauts. Employing this strategy will greatly accelerate and increase scientific return while substantially lowering costs and risks.

Providing scientists with a high degree of situational awareness and adaptive capabilities requires high sensory bandwidth and low communications latency. This is achieved by placing humans in habitats that are sufficiently proximal to the exploration target, whether orbiting above or in a nearby (sub)surface habitat. With scientists exploring from a radiation-shielded, shirt-sleeve habitat, preparation/recovery time, hazards, and consumable limitations associated with EVA operations are eliminated and productivity soars. By employing this LLT strategy, a synergistic partnership between humans and robots is achieved.

Planetary protection goals are aided in advance of astronaut landings by using LLT to control sterile robotic surrogates on the surface. When humans do physically land on an off-Earth exploration destination, LLT also multiplies their effectiveness far beyond the limitations of EVA traverses, expanding their reach to many more sites.

In this report, applications to planetary science are formally examined, and the enabling cases for other exploration disciplines such as infrastructure emplacement are also considered. Included are the conceptual and practical foundations of LLT, opportunities for using derivative approaches for scientific off-Earth exploration, and circumstances under which planetary science employing telepresence would be especially productive.

An important finding from these workshops is the conclusion that there has been limited study of the advantages of conducting planetary science via LLT. This report recommends that space agencies such as NASA substantially increase planetary science return with greater investments in LLT research, field tests, and applications when actually sending humans to off-Earth exploration sites.

A New Era of Planetary Field Science

The most fundamental questions in planetary science concern the formation of our solar system and the possibility of life on other planets. These questions are best addressed when the human mind can immersively interact with an alien surface. LLT offers us a chance to engage in distant exploration sooner rather than later, proving the value of human explorers in our quest to understand our solar system.

LLT presents a relatively low cost, low-risk next step for space exploration and provides the most effective way to accomplish the science goals of geologic field study on distant planetary surfaces. Taking advantage of the combined strengths of autonomous systems, teleoperated systems, and human operators (Figure 9.1), LLT can be the means paving the way for humans to safely explore virtually anywhere off-Earth.

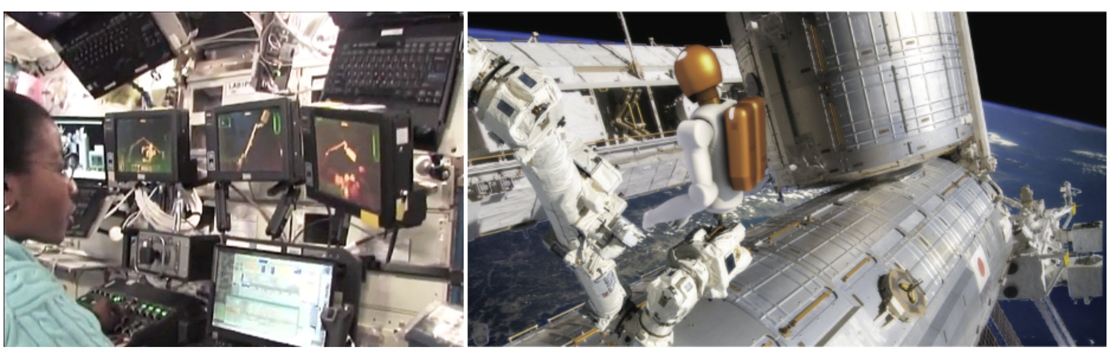


Figure 9.1: (Left) Astronaut Stephanie Wilson controlling Canadarm. (Right) Robotnaut 2 operating on the International Space Station (Images: NASA).

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Appendix A: Historical Background

The premise of space exploration low-latency telepresence (LLT) has not been generally considered, but it does have some substantial background. It is important to review this background, to put the results of this study in proper context.

- The October 1928 issue of "Amazing Stories" includes a contribution by J. Schlossel titled "To the Moon by Proxy" in which exploits of a robot on the Moon operated by a scientist on Earth are portrayed.
- The 1942 Robert Heinlein short story "Waldo" paints a clear picture of telepresence in space, with a human in a habitat exercising human presence on a planet below.
- The uses and development of robotic systems and teleoperation for space activities are reported on in "Machine Intelligence and Robotics Report of the NASA Study Group," September 1979.
- In the 1980s, Marvin Minsky (MIT) proposes to NASA that operations on the space station could largely be done by teleoperations from the Earth.
- Fred Singer, in his 1984 "PH-D Project" (Phobos and Deimos) suggests Mars-surface teleoperations from Martian satellites.
- The NASA Technical Memorandum, Volume II, March 1985, "Advancing Automation and Robotics Technology for the Space Station and for the U. S. Economy" defines and describes uses for teleoperation and telepresence, and the research and development areas needed to be pursued back then.

- The Paine Report (1986) by the National Commission on Space proposes a "Bridge Between Worlds" strategy that includes teleoperation as being a potentially powerful tool for space exploration. The report presumes that only Earth-based controllers would be available and specifically recommends that:
  NASA explore the limits of expert systems, and tele-presence or tele-science for remote operations, including ties to spacecraft and ground laboratories. In working toward these goals, a broad examination of the non-space applications of tele-science should be included.

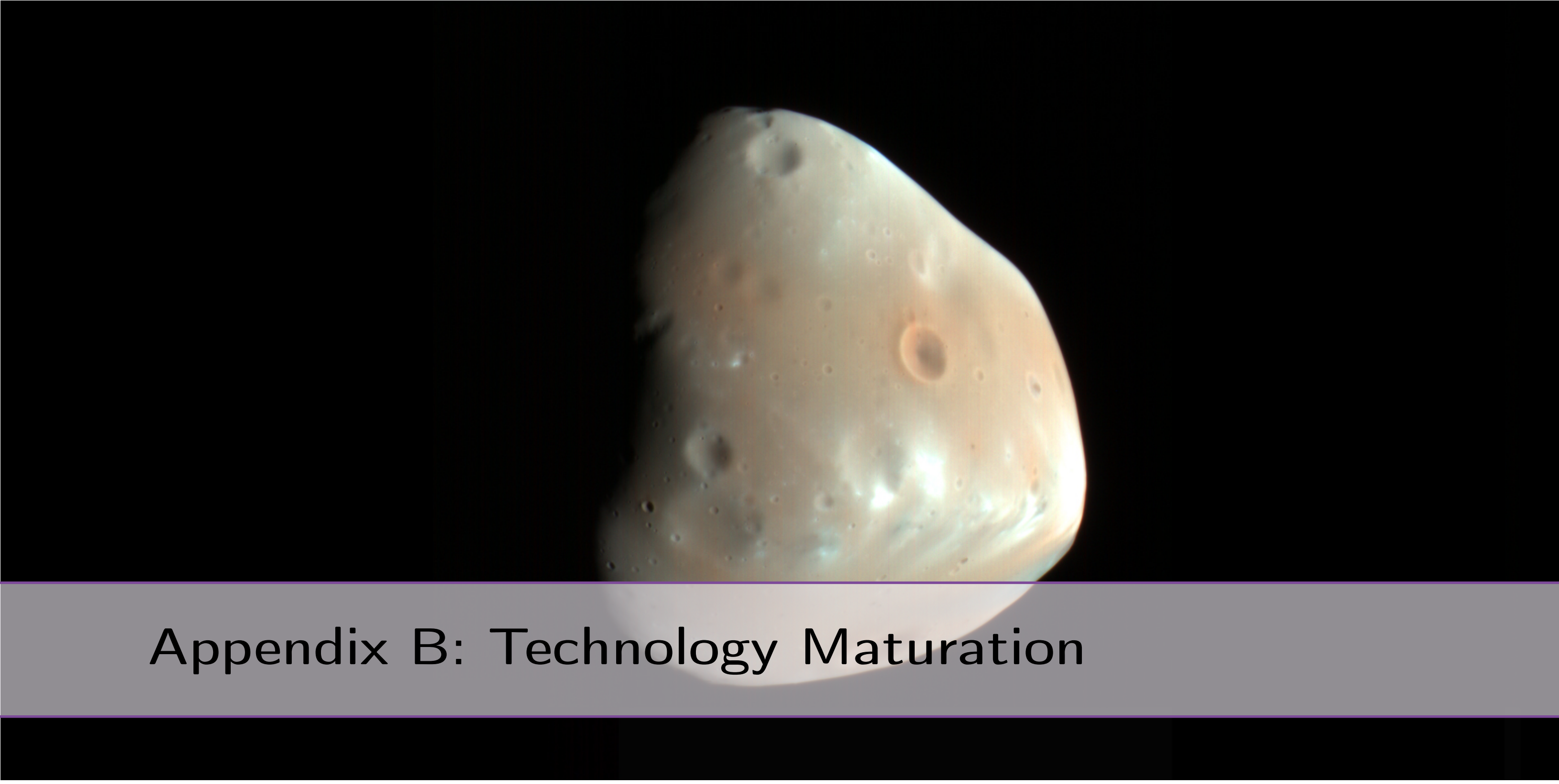
  Wherever practical, use tele-operation from Earth to control and guide production, maintenance, and transport. Because of signal travel times, tele-operation is practical in the Earth–Moon system, but not far beyond.

- The 1989 NASA "90 Day Study on Human Exploration of the Moon and Mars" presumes telepresence robotic deployment of infrastructure, and telepresence robotic exploration of larger areas controlled from a surface outpost.

- The full concept of LLT is better fleshed out in the Stafford (or "Synthesis Group") Report in 1991. This high level report is constituted to develop a thorough concept for the Space Exploration Initiative proposed by the President. They note that:

  "Telepresence" robots can conduct some geologic fieldwork. While such a technique might greatly enhance the scientific return, the details of how such robots might work with people remain to be developed. Operators for these telepresence robots need near-instant radio contact with the robots. This may be marginally obtainable by having the controllers on the Earth, but operators on or near the Moon have a near-zero time lag for robotic teleoperations. An operator located at an Earth/Moon Lagrange point (L1), for example, would have complete line-of-sight radio access to almost the entire near side of the Moon. Teleoperations from this vantage accomplish significant field exploration by projecting human powers of thought and observation into the robotic alter ego on the surface. This operations concept is particularly valuable at Mars, where telerobotic control from Earth is not feasible because of the great time lag in radio communications".

Such telepresence robotics are considered by the Stafford Report as a supporting technology that is identified as key for future exploration.



Appendix B: Technology Maturation

Early enthusiasm for LLT arose when technology and engineering were simply not ready to support it. LLT was considered a "good idea" that faced tremendous technological and engineering hurdles. For instance, remote imaging, which used to be a matter of power-hungry and heavy video cameras, can now be achieved with highly sensitive, low-power, and high-resolution cameras. Telepresence robotic engineering has seen, in the last few decades, remarkable advances in dexterity to the point where LLT dexterity is now better than that of a human with EVA gloves. Developments in imaging, dexterity, and mobility, as well as communication technologies, have now largely surmounted all of these hurdles. The commercial and military world routinely applies LLT, and it is a rapidly growing industry.

The 2007 "NASA Exploration Blueprint: Data Book," a Johnson Space Center effort to provide organized input into an integrated space plan, referred to LLT as an exploration feature that would feed forward from cislunar space to high Mars orbit. This would provide "optimized robotic and human operations—dramatically higher productivity; on-site intelligence".

The 2009 "Human Exploration of Mars Design Reference Architecture 5.0" is a baseline document for human spaceflight planning for Mars. This document highlighted the importance of teleoperated robots, but seemed to consider only such teleoperation from surface outposts. The astronauts would, in this respect, be considered "telecommuters."

The 2012 "NASA Technology Roadmap" is explicit about the potential of LLT:

The top technical challenges in human-robot interfaces are full immersion telepresence with haptic, multi sensor feedback, understanding and expressing intent between humans and robots, and supervised autonomy of dynamic/contact tasks across time delay.

In May 2012, a two-day "Exploration Telerobotics Symposium" was held at NASA's Goddard Space Flight Center that highlighted the promise of LLT robotics for space exploration. The final report is available here:
`http://spirit.as.utexas.edu/~dan/GSFC_2012_Telepresence.pdf`

The promise of this strategy has been considered by the NASA Human Spaceflight Architecture Team (HAT) for the agency Evolvable Mars Campaign. However, this work analyzed science accomplishment in a limited context, and primarily assumed humans at Phobos. Group leader Lupisella is part of the KISS study reported here.

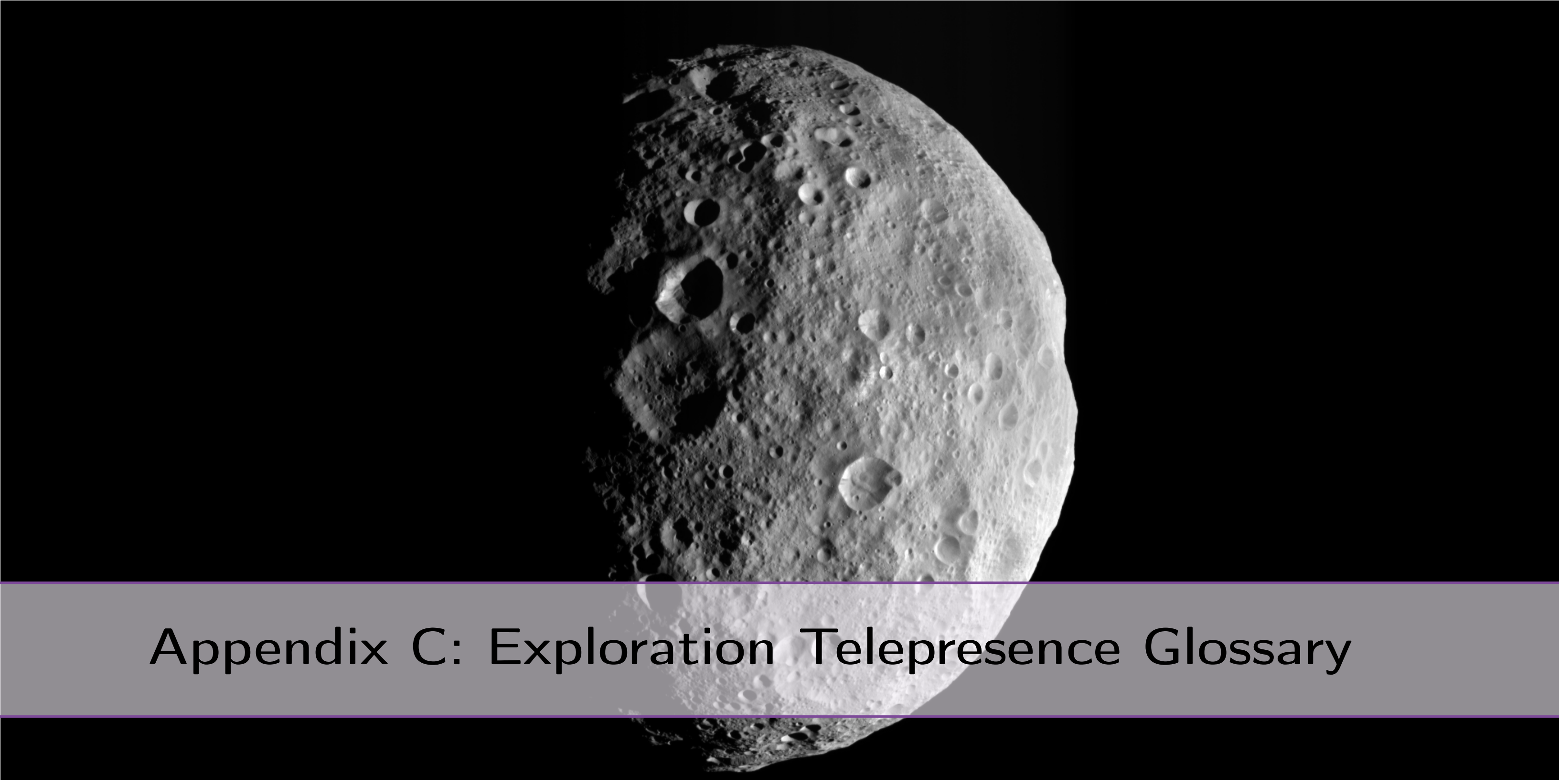
Efforts are underway to perform LLT in a space environment. Several years ago, The German Aerospace Center implemented ROKVISS, which allowed LLT control of instrumentation on ISS from the ground. This has been followed with KONTUR, which allows LLT control on the Earth from ISS. ESA's METERON SUPVIS provides low-latency supervised autonomy on the ground, controlled by ISS. This work is represented on this KISS study team by Li and Artigas.

Supervised autonomy experiments investigating handover and handback between telepresence control and autonomy for planetary prospecting robots were conducted at Carnegie Mellon University by study member Podnar in 2005. These experiments operated early K10 robots locally and remotely at NASA Ames, and remotely operated the Sample Return Rover at NASA's JPL.

NASA has developed control systems enabling astronauts on ISS to operate a K10 rover on Earth KISS study member Fong leads this effort. These projects demonstrate practical telepresence for low Earth orbit and address the kinds of communication challenges that will be encountered doing LLT on other worlds.

With respect to this ISS work, the 2013 "Global Exploration Roadmap" noted that:

Low-latency telerobotics demonstrations planned for the ISS will evaluate the benefits of using crew in orbit around a planetary surface to perform high-value exploration activities by controlling robots on the surface.



Appendix C: Exploration Telepresence Glossary

Definitions in this glossary reflect consensus arising from personal and emailed interactions between participants in the KISS workshops, "Human Exploration and Space Science Augmented by Low-Latency Telepresence (LLT)", held October 2016 and July 2017.

Underlined terms in definitions are themselves defined in this glossary.

Augment: to render greater through contributed attributes. In this study, LLT is expected to augment space science productivity, as opposed to enabling it, because "enabling" incorrectly implies LLT is a prerequisite for space science.

Autonomy: in the context of this study, a robotic system exhibits this quality to the degree it functions independently from planned human supervision or human intervention in response to an unexpected event. Robotic systems have effectively no autonomy when being used for telepresence. A human exhibits autonomy in conduct of space science to the degree that productivity is not compromised by consultation with other humans or robotic systems. Other terminology relating to mixed human/robotic autonomy includes telesupervision, supervised autonomy, sliding autonomy, multi-level autonomy, and semi-autonomy.

Cognition: acquisition of knowledge and understanding through experiment, observation, sensation, thought, and recalled experience.

Consensus: general (but not necessarily unanimous) agreement.

Dexterity: skill in performing manipulative tasks with hands. In the scope of this study, "hands" can be human or robotic depending on context.

Exploration: remote or proximal actions to capture knowledge regarding a relatively unknown venue with the intent of pointing the way for future forays. These actions are distinct from ones associated with "pioneering", "settlement", or "colonization" because such ventures intend to establish a permanent human presence at a previously explored venue.

Foveation: the process of selecting higher resolution imagery from a scene according to one or more fixation points defined by a human operator's vision.

Haptic: relating to forces sensed during contact with objects. Sensed forces may relate to the local environment (exteroception) or to balance and posture (proprioception).

HLT: high-latency telerobotics. See Latency.

LLT: low-latency telepresence. See Latency.

Latency: the time delay between cause and effect. In the contexts of data transmission and this study, latency is the round-trip light time, plus communication systems delays, between a telepresent human and a science target under study. Depending on the specific telepresence task, latency becomes humanly unperceived below a delay threshold from 200 ms to 500 ms. Unperceived delays associated with remote performance of a task are termed in this study as the condition of low-latency telepresence (LLT). Appreciable delays (measured in seconds to days) associated with remote performance of a task are collectively termed in this study as the condition of high-latency telepresence (HLT). Some marginal HLT tasks with latencies as high as 900 ms to 2.6 s can be performed with humans in continuous control of robotic proxies. At still higher latencies, some degree of robotic autonomy at the task venue becomes necessary.

MLT: moderate-latency teleoperation. See Latency.

MTBI: mean time between interventions, a metric associated with quantifying the degree of autonomy achieved by robotic systems or humans.

Productivity: in the contexts of space science and this study, productivity may be characterized by any of multiple metrics. These include time available to acquire data, the time rate at which data are acquired (such as ground speed or science targets investigated per unit time), MTBI, the quality of acquired data, and the contextual scope of acquired data.

Proprioception: the sense of self-movement and body position. The central nervous system integrates information from proprioception and other sensory systems, such as vision and the vestibular system, to create an overall representation of body position, movement, and acceleration.

Real Time Control: see Latency and its discussion of LLT.

Recorded Reality: a reproduction of an environment in which passive viewing from various perspectives can be conducted. However, user physical interaction with the reproduced environment is not possible. Sometimes "recorded reality" is associated with "virtual reality".

Situation(al) Awareness: ongoing cognition, through sensory input and recall, of contextual relationships between threats and objectives relating to mission success, an evolving timeline of prioritized tasks, and the surrounding environment at multiple spatial scales. In general, enhanced situation awareness produces greater science productivity. When combined with LLT, enhanced situation awareness reduces the level of robotic autonomy needed to accomplish a specified task.

Sixth Sense: in the context of this study, the degree to which situation awareness is achieved such that telepresence is rendered transparent (and possibly enhanced) with respect to human in situ presence, particularly when a pressurized garment is necessary for that presence. The sixth sense develops as a consequence of operational experience and confidence it instills. It may also be the product of technology, such as multispectral vision or omniscient aerial views of a worksite, transcending what human senses alone can directly perceive.

Supervised Autonomy: mode of teleoperation in which limited human intervention is planned. See Autonomy.

Tactile: relating to the sense of touch. In the context of this study, tactile specifically relates to sensing texture, temperature, heat conduction, liquid flow, or vibration when in contact with a solid object or immersed in a fluid.

Teleoperation: human control of distant apparatus to perform actions using transmitted commands and teleperception or telesensation. See Telerobotics and Telepresence.

Teleperception: human cognition at a distance using received data. See Telepresence.

Telepresence: a cognitive sensation of being elsewhere for the purpose of participation in distant events.

Telerobotics: control of distant apparatus to perform actions.

Teleprogrammed: telerobotics using transmitted programs. Commonly employed in high-latency situations.

Telesensation: human cognition at a distance using received data. See Telepresence.