AN EDUTAINMENT BASED LUNAR MISSION AND RELATED SPECTRUM ISSUES

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Abstract

Carnegie Mellon University has proposed a robotic lunar mission which will last two years and cover 1000km on moon and revisit several historic sites. Unlike traditional space exploration missions, which have been concerned primarily with science, the Lunar Rover Initiative focuses on edutainment (entertainment and education). With the transmission of live panoramic video, participants will be provided the opportunity for interactively exploring the Moon. Participants include visitors to theme parks or science centers, TV viewers, school kids, and internet surfers. These visitors will be immersed in a live lunar telepresence previously had only by heroes of the Apollo program who set foot on the Moon. In addition to NASA, sponsors may include theme parks, marketing firms, TV networks and scientists. With state-of-the-art robotics technology, the mission will bring lunar exploration, experience and science to the masses. The requirement of telepresence demands high data rates. This is challenging since the power available on the rover and spectrum bandwidth allowed is limited. This paper presents an overview of the mission, unique communication scenario and related spectrum issues.

1. Introduction

The Lunar Rover Initiative (LRI), undertaken by the Planetary Robotics Program at the Robotics Institute, Carnegie Mellon University, is chartered to place a robotic vehicle on the Moon before the year 2000. Endorsed by NASA as part of the Telerobotics Program in Code X, the LRI has chosen a mission focused on providing entertainment and education, or "*edutainment*", rather than the science agenda of traditional space exploration. The main product of the mission is high-quality, panoramic, color video returned to Earth and displayed in real-time, which is suitable for movies, television broadcasts, CD-ROMS, and photographic stills, and when combined with the rover motion history can be used to generate highly realistic telepresence experiences or inputs for geological analysis. The goal of the mission is to increase awareness about robotics and planetary exploration among mass audiences and to demonstrate success of low cost space missions.

2. Motivation

Nearly a quarter century has elapsed since the last lunar landing, and the Moon remains an exotic world. Aspirations to retrace the footsteps of the Apollo missions and its astronauts have yet to succeed. The LRI proposes a robotic lunar mission to give the experience of exploring the Moon to millions of interested people through live tele-experience. With enormous launch costs and restrictive launch vehicles the primary barriers to viable space enterprise, it will be years before sustained human presence in space becomes commercially viable. Meanwhile, space activity can be expanded through robotic devices which generate commercial enthusiasm by performing novel or cost saving tasks like satellite repair or planetary exploration. Future generations of robotic devices can lay the groundwork and construct habitations for human presence.

Traversing the Moon is within reach of current mobile robot technology. The surface is stable and barren, which suits current perception and navigation systems. A direct line of sight between the lunar near-side and the Earth is always available for maintaining communication. Without a filtering atmosphere or clients, sunlight is a rich and guaranteed power source. Low radiation levels make usage of state-of-the-art computing and electronics possible. The low time delay between Earth and the Moon makes real-time human interaction and remote operations possible.

In summer 1995, Carnegie Mellon demonstrated the required terrain navigation and safeguarding technology in a 10km traverse on rough, lunar analog terrain. This follows a 1 km traverse in 1994 and precedes a 100km traverse in 1996. An Earth analog of the design will be demonstrated in a 1000km traverse part of mission readiness evaluation in 1997.

3. The Mission

The LRI mission involves a 1000 km journey by a pair of semi-autonomous, teleoperated, unmanned lunar rovers over a two year period starting in the August of 1999. The pair of robots will visit five historical sites during the traverse, starting at the first manned lunar landing site, Apollo 11. The trip then passes by the

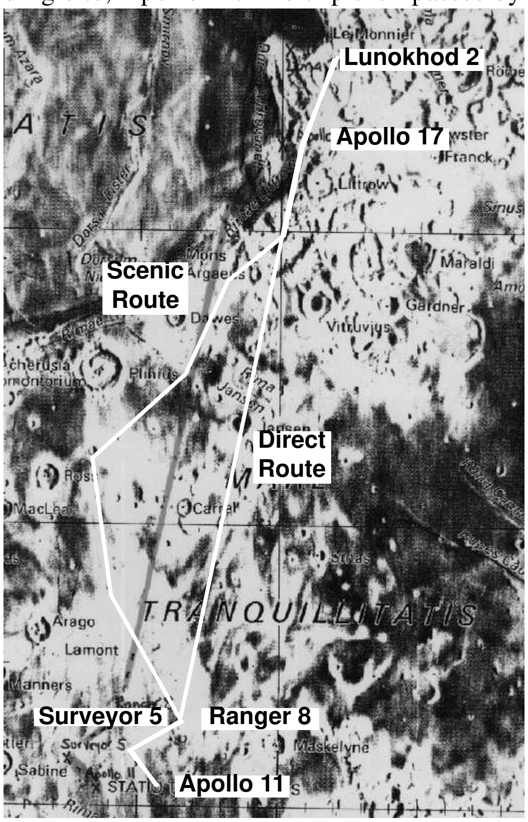

FIGURE 1 Traversal route and historical sites

impact crater of Ranger 5 and the landing site of the unmanned Surveyor 8 probe and crosses the Mare Tranquilitatis (Sea of Tranquility). Climbing into the lunar highlands, the rovers will visit Apollo 17 (the last manned lunar landing site) and then quest for the landing site and grave of the Soviet Lunokhod 2 unmanned rover.

After completing the planned traverse, the rovers will continue to explore interesting sites until catastrophic failure occurs. With the mission successfully completed, slightly higher risks can be taken, resulting in traversals of more extreme terrain and more impressive video return. Possible continuation targets are the Taurus Mountains and the huge crater of Posidonius 500 km to the north or the Haemus Mountains and the Apennines about a 1000 km to the west.

4. Rover Technical Summary

The mission is accomplished through the use of two identical rovers (Figure 2)which traverse 1000km while visiting historic sites on the Moon. High resolution,

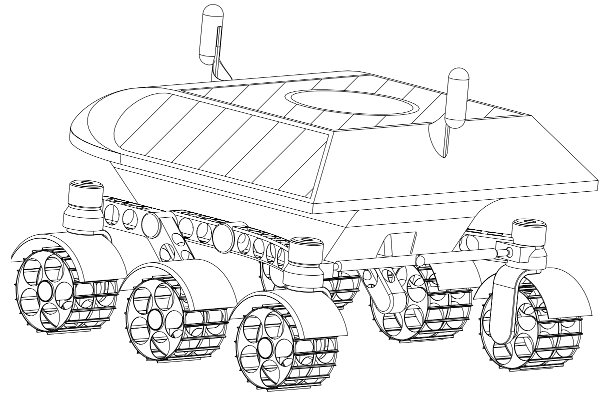

FIGURE 2 Lunar rover for CMU mission

immersive, panoramic video is acquired through omnidirectional “pano-sphere” optics and compressed using wavelet algorithms. Telemetry and video are transmitted to Earth simultaneously by both rovers using right and left circular polarization from an X-band phased array antenna with 60 degree electronic beam-steering, and a low-gain omnidirectional antenna is used to receive command information. The rover is heated using plutonium heat sources and AMTEC (alkali metal) is used to convert the heat to electrical power. Custom designed multi-chip modules provide the computing power and are based around rad-hard R3000’s and single-chip multi-processor DSP’s (i.e. the TI MVP-C80). The rover is composed of aluminum ribs mounted on a honeycomb base-plate and wrapped in a fabric layer of kevlar and kapton sheeting (3 layer MLI). Terrainability is achieved using an explicitly steered six-wheeled distributed drive chassis with passive-linkage rocker-bogie suspension (Figure 3). Each rover is 2m x 2m x 1.2m, weighs 238kg, uses 540 Watts, and it costs 59.8 Million to develop and fabricate two rovers.

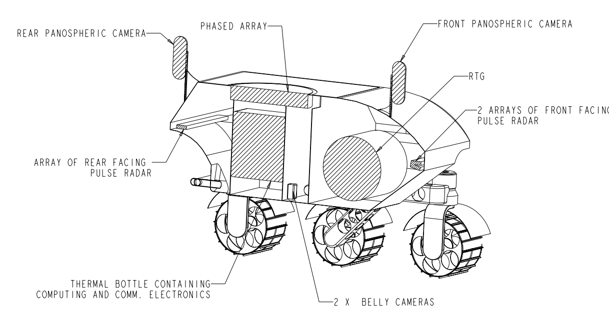

FIGURE 3 Cut out of Lunar rover

The two rovers operate primarily in a leap-frog scenario (one rover remaining stationary and observing the exploration of its partner and then reversing roles) with role transitions occurring the shorter of 250 meters or 30 minutes. The rovers operate continuously, even during the fourteen Earth-day lunar nighttime (seen as a new moon from Earth). The average speed of the rovers during the traverse will be 0.3 m/s, a slow hiking pace. While exploring, the rover is mostly teleoperated from earth (the round trip time-delay is about 5 seconds) by an amateur driver. During this time, the rover must safeguard itself from unforeseen events, human error, and deliberate operator mischief. Each rover is thermally regulated with self-power distribution, and is also responsible for managing the communication link integrity and imaging quality. The pair of rovers will reach the Moon via Proton launch vehicle and Phobos lander.

5. Schedule

Following the September 1995 preliminary design review, the terrestrial demonstration will occur in May 1997. Predicated on available funding, the Critical Design Review would then be scheduled for July 1997. With approval at this time, component ordering begins, along with the construction of the engineering mock-up, software verification and subsystem integration, with a September 1998 deadline for accepted and tested components. After the final US system testing and preliminary acceptance, the rover is shipped to Russia in December 1998. The power system integration and final systems evaluation should be completed by February 1999 with acceptance testing completed in March 1999. After three months of lander integration, launch can occur in June 1999. This allows one month of slippage in the schedule to still be at Apollo 11 on its 30th anniversary.

6. Communication Requirements

The primary purpose of the mission is to entertain and educate. Therefore, the return of imagery which excites and intrigues is the major product. Rather than limiting audiences to one narrow view, the rover will return omnidirectional information so that each viewer can personally choose where to look. In addition, a science payload when combined with the imagery and rover sensor data will yield the most comprehensive survey of the lunar terrain to date. It is important then to be able to support high data rates. The main objective of the communication system is to support high data rate reliably over the duration of mission operations. Based on this, the main communication requirements are:

- The two rovers should be able to transmit at the minimum data rate of 7.5 Mbps simultaneously.
- The rovers should be able to receive commands from an Earth station at all the times at the rate of 0.5 Mbps during mission duration.
- The bit error rate (BER) should be less than 10^{-6}.
- 99% of transmitted power must be contained within assigned RF bandwidth (FCC regulation).

7. Frequency Selection

Various bands (S, X, Ku, Ka) for space research were considered and analyzed. With the limited power available at the rover, Ka-band does not serve the purpose due to very high rain attenuation. S-band and X-band are preferable due to low attenuation. Although Ku-band has higher attenuation than S-band and X-band it can be used. The main difficulty is that the bandwidth allocation is not guaranteed in this band. Also, S-band is reserved for government/military use.

After preliminary discussions with the OSC (Office of Space Communications, NASA HQ) and the FCC, X-band (Space research band- 8450-8500 MHz) appears to be the best choice. The maximum allocation allowed in this band is 10 MHz. Using Nyquist QPSK modulation and rate 2/3 turbocode for error correction, the requirement of 7.5 Mbps and BER of 10^{-6} can be achieved. Table 1 summarizes the downlink spectrum requirements.

Frequency	8490-8500 MHz
Bandwidth	10 MHz
Polarization	Right hand/Left hand Circular Polarization

TABLE 1 Frequency requirements (Downlink)

The uplink requirements is 0.5 MHz. Currently there are no allocation in X-band for space research and the allocation in S-band are exclusively for deep space network (DSN) usage.

8. Communication Scenario

Downlink communication from the rover to earth is achieved using a phased array antenna operating in X-band, with a low-gain omnidirectional antenna for the uplink and as downlink backup (Figure 4). The 683 element antenna (0.55 m diameter) is capable of electronically steering the beam up to 60 degrees from the vertical. The steering vector is computed using a star-tracker and inertial measurements. The downlink transmission is modulated using Nyquist QPSK to bandlimit the signal within the allocated frequency range. One rover utilizes right-hand circular polarization

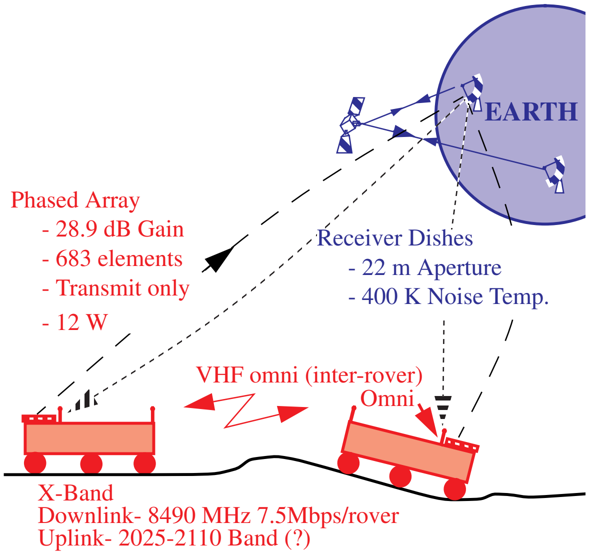

FIGURE 4 Communication Scenario

which the other uses left-hand to allow both rovers to communicate simultaneously while sharing the same frequency range. Error correction is accomplished via a rate 2/3 turbocode, and the anticipated bit-error-rate is 10^{-6}. Three ground stations with a 22m parabolic antenna are required around the world (possibly US, Russia and Australia) to maintain continuous communication. The transmission is then relayed via satellite to the current control station location. In case of an uplink or downlink failure, that rover can relay its transmission through the other rover by using the inter-rover omnidirectional antennas (broadcasting in the VHF range).

The link budget for the downlink is shown in the following table.

Parameter	Value
Frequency	8.495 GHz
Data Rate	7.5 Mbps
Transmitter Diameter	0.55 m
Transmitter Gain	28.9
Transmitter Power	12 W
Beam Width	3.6 deg
Receiver Diameter	22 m
Receiver Gain	63.6 dB
Noise Temperature	400 K

TABLE 2 Link Budget

Parameter	Value
EIRP	35.7 dBW
Flux Density	-148.7 dBW/m^2
Eb/N0	6.7 dB
Required Eb/N0	2.0 dB
Link Margin	4.7 dB

TABLE 2 Link Budget

The link margin of 4.7 dB is adequate for X-band. The EIRP and flux density are reasonably low and should not interfere with other signals.

9. Spectrum Issues

LRI is a unique mission which involves participation from NASA, university and several companies. Although NASA is a part of the mission, it is not considered as a government mission due to involvement of private companies. Hence, LRI is the first non-governmental mission to the moon and no clear policy exists regrading spectrum allocation for such missions. Spectrum allocation is a bottleneck for the LRI and similar missions and a clear policy and reserved spectrum will be very useful. Some specific issues are:

Uplink Frequency: There are no uplink frequencies for space research for non-governmental usage.

Bandwidth: Though 10 MHz (maximum allowed) in X-band for space research is enough for most of the missions, it may fall short for missions like LRI.

Mission duration: Given the experimental nature of the LRI mission, and the fact that it will be concluded within two years after launch, are there (or should there be) separate experimental frequencies which could be used for this mission or similar missions?

An additional issue relates to international coordination. For space exploration, a small beamwidth covers entire Earth. Also, it requires several stations around the Earth to track such missions at all times. It might be useful to have an agreement between all the countries regarding spectrum usage for such missions.

10. Closure

In the next century, the moon will be a venue for space exploration due to scientific and commercial opportunities. Carnegie Mellon is developing robotic technologies to enable exploratory missions and to establish permanent robotic activity on the moon, including robots for resource prospecting and utilization, and construction. Lunar Rover Initiative is first in the series of lunar missions. To demonstrate the technology required for lunar exploration, CMU is performing a terrestrial demonstration in 1997. Also, the process of application for downlink frequencies is in progress. Several options for uplink frequencies are being evaluated and no suitable frequencies are identified so far.

Acknowledgements

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