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Continuous Communications to the Moon's South Pole

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Landing sites near the South Pole of the Moon have been proposed for the upcoming Lunar Precursor and Robotics Program (LPRP) and eventual return to the Moon. Direct line of sight from the lunar South Pole to Earth either does not exist at all, or exists only periodically in many of the areas of interest. This paper will investigate several different communications architecture that enables lunar South Pole communication to Earth, including surface-to-lunar-relay, direct line of sight, and surface-to-Earth-relay.

I. Introduction

Great interest has been generated in the lunar South Pole by the discovery of signatures of hydrogen gas. It is proposed that permanently shadowed craters of the lunar South Pole contains water ice, which gives rise to the high H concentration. If proven, locations of water ice on the Moon will drive future exploration and resource utilization missions, and determine the location of proposed lunar outposts. The lunar South Pole also contains high ridges which lie in continuous sunlight, enabling round the clock solar panel operation for efficient resource extraction or power generation. We are therefore interested in methods of establishing continuous communication with the lunar South Pole. In the past, communications with the moon was achieved via direct line of sight, since both crewed and robotic lunar landings have been in the equatorial region of the lunar Near Side. Direct line-of-sight from the Earth to the lunar South Pole, however, is intermittent due to varying declination of the moon over each 27 day orbital period. Especially challenging is communication with crater floors on the lunar South Pole, where the proposed water ice resides. We present in this paper a discussion of the communications architecture trade space to enable both communication with assets located both on sunlit ridges and shadowed crater floors.

The communications architecture consists of two categories: relay communications with Earth, and communication with the crater floor. The division is a result of the very different communications requirement and environment for the surface of the moon and the deep crater floors. We envision future lunar surface exploration missions to consists of combinations of landers and/or rovers. We use the term landers to refer to fixed lunar surface assets, and rovers to refer to mobile lunar surface assets. Exploration of the crater floor is assumed to be performed by rovers, and all cases of crater floor communication may be referred to as rover communication. Methods to achieve relay communications with Earth include using lunar relay ground stations, lunar relay satellites, relay satellites located at a Earth-Moon Lagrange point, and relay satellites in Earth orbit. Methods of rover communication include using low frequency ground waves, fiber optic lines, cell-phone-like relay stations, or some combinations of these systems. We present details of each piece of the architecture, and trade options not immediately unfeasible are evaluated on the basis of cost, risk, data volume capability, availability, and extensibility to future missions.

II. Communication Architecture Trade Space

Shown in Figure 1 is a summary of the lunar South Pole communications trade space. We have included specific assets such as the Lunar Reconnaissance Orbiter (LRO), and the Tracking and Data Relay Satellites (TDRS) as shorthand for assets having similar orbits and data handling capability. Lunar South Pole communications requirements are summarized in Table 1. The requirements are derived from meeting top level LPRP program requirements.

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Table 1: Top Level requirements for lunar South Pole communications.

Requirement
high data volume, at least Mb per day
coverage of area with no direct Earth line-of-sight
demonstrate extensibility to future mission
contribute to lunar outpost infrastructure

Evaluation methods of the trade space options are shown in Figure 2. The weighting is distributed evenly across the five categories:

- **Cost**: the cost of adding the capability (e.g. an optic fiber tether) or placing the infrastructure (e.g. a cell relay tower). This only includes costs associated with developing, building, and operating the trade option, and does NOT include launch vehicle and mission development. This cost is a relative scale for the trade options investigated.
- **Risk**: the risk level of the trade option, including heritage, TRL, and the uncertainty associated with operation on the lunar surface. The risk is also a relative scale.
- **Data Volume**: return per day, low is defined to be a few kb per day, and high is Gb per day.
- **Availability**: accessibility to command and control, refers mostly to percentage of time orbiting assets has LOS with Earth and with its lunar surface partners.
- **Extensibility**: the utility of the trade option to future lunar exploration missions, whether from a technology demonstration point of view, or actual placed infrastructure.

Earth – Moon Comm relay	Relay Sat.	Line-of-Sight	Ded. Mission	LRO
Rover to Earth relay	Satellite Relay	Lander Relay	Direct Earth	
Line of Sight Relay	Cell Tower Relay	Fiber optic	Groundwave	Cell/Fiber combo
Orbiter Relay	Dedicated Orbiter	LRO	TDRS	
Orbiter orbit	Polar Orbit	L2	Inc. Elliptical Orbit	South Pole Halo Orbit
Comm Bands	S Band	K Band	Ka Band	Laser Comm

Figure 1. Top level lunar South Pole communications architecture trade space. Yellow highlights indicated currently viable trade space options.

III. Relay Communications

The relay communications options are summarized in Figure 3. We discuss each option in depth.

Value / Criteria	1	2	3	4	5
COST (20%)	Very High	High	Medium	Low	Very Low
RISK (20%)	Very High	High	Medium	Low	Very Low
DATA VOLUME RETURN/Day (20%)	Very Low	Low	Medium	High	Very High
AVAILABILITY (Cmd & Control Accessibility) (20%)	< 10 %	10-25 %	25-50%	50-99%	100 %
EXTENSIBILITY (20%)	Very Low	Low	Medium	High	Very High

Figure 2. Evaluation criteria for lunar communications architectures.

A. Low Altitude Polar Circular Orbit

Lunar circular orbits are stable, and well known; most existing lunar orbiters were placed in circular orbits with 150 to 1000 km altitude. Higher or lower orbits may be maintained for small amounts of propellant near the stable region, and increasing amounts with increased deviation. As little as three spacecrafts can provide good coverage for an altitude of 2,000 km near the equator or the poles. However, for continuous lunar converge as many as 100 satellites would be required, assuming an altitude of 2,000 km.[1]

The primary advantage of low altitude circular orbit is the possible high data rate transmission with ground assets due to shorter ranges, and capable of communicating with Earth during at least 50% of the orbit period. The main disadvantage is the short contact time with rover, especially inside a crater. See Table 2 for a comparison of the orbital coverage for different representative circular orbits, and Molniya orbits (discussed next).

Low Altitude Polar Circular Orbit (e.g., LRO)	Molniya (Elliptical Inclined) Orbit	L1/L2 (Earth/Moon)	Earth Orbiting Relay
<u>Advantages</u> Cost (if LRO) Higher link Data rates (short Distances) <u>Disadvantages</u> Short rover Contact time with each Satellite (<10%?) Must have "store and dump" Capability	<u>Advantages</u> Longer contact times and higher % cover-ages with each Satellite (up to 70% with one) <u>Disadvantages</u> Cost (not LRO)	<u>Advantages</u> Global coverage with four satellites <u>Disadvantages</u> Further away (lower data rates) and less Contact than Molniya (poor limb coverage) High cost & complexity (operations)	<u>Advantages</u> Line of sight to near side of Moon greater than 97% possible, for single relay. May be able to periodically look over limb by small amount. <u>Disadvantages</u> Offers only slightly better views of lunar southern polar region. High cost, little benefit for uncrewed exploration.

Figure 3. Lunar orbital relay options and their main advantages and disadvantages.

B. Frozen Orbits

The term "frozen", refers to an orbit that does not require ΔV to maintain desired attributes. An infinite number of frozen orbits exist around the Moon.[2] Of interest are high inclination elliptical orbits. We would like a relay that is in view from deep craters near the South Pole for a large percentage of the time. This would mean that the relay would need to at a point below a plane tangent to the lunar South Pole. Nearly all of this region has continuous line of sight to Earth.

An elliptical orbit with an inclination of 90°, and an argument of periselene of 90° would provide the best coverage. However, the periselene of this orbit would precess and move its aposelene, such that it would move away from the South Pole. A type of frozen orbit called Molniya is inclined such that periselene, aposelene, and argument of periselene remain relatively constant. For those missions that require continuous communication, a second relay satellite can be placed in the same orbit, with periselene separated by one half orbit. If redundancy is necessary, a third relay could be added.

C. Lagrange Points

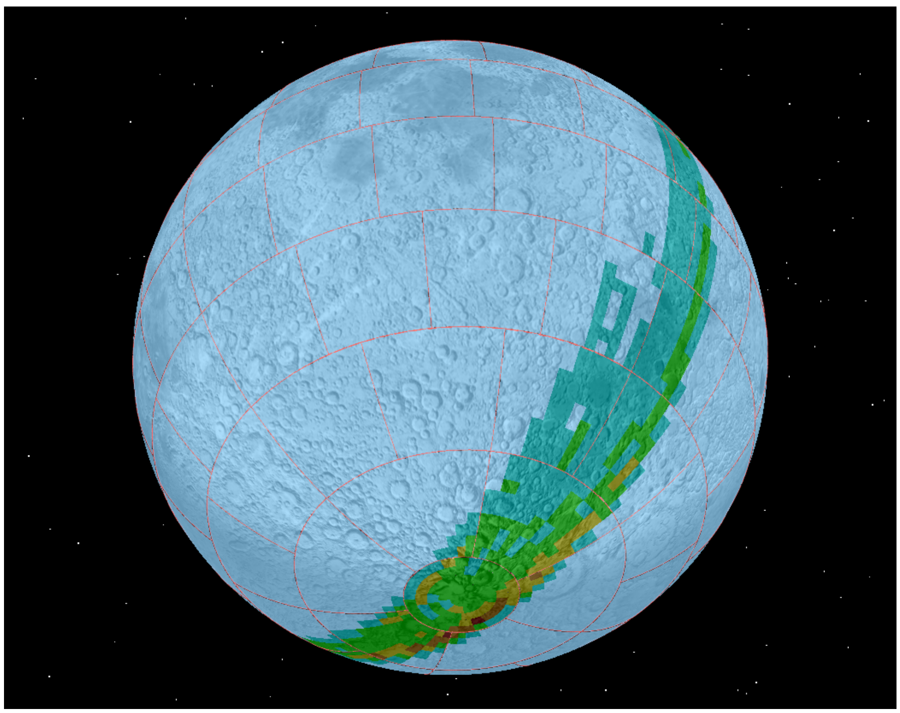

Figure 4. Converge provided by constellation of four Lagrange point relay satellites.

Using Lagrange points for lunar communications was first proposed as early as 1967.[3] Two spacecraft, one each at Earth-Moon L_1 and L_2, would be able to provide continuous coverage for most of the surface of the Moon. Four spacecraft would provide global coverage over level terrain – but coverage over deep craters near the limb of the Moon would be poor. Figure 4 shows that coverage over most of the surface is 100% (in light blue), but can dip below 90% (in red) near the limb. The surface transmit power would be less than required for direct to Earth communication, but more than the power required to transmit to a lunar orbiting relay, assuming the same data rates. The ΔV for maintaining such orbits would be very small – but weekly maintenance of the orbit would be necessary. However, the primary drawback is the high cost of a separate launch or launches to the Earth-Moon L1 or L2 points. Also the cost of four satellites for non continuous coverage is prohibitive.

Table 2: Contact duration for various lunar orbits. Two orbit types are considered: circular and Molniya. The contact times are given in minutes for a location inside a crater center, and also Mt. Malapert, which is an example of a continuous sunlit ridge in the lunar South Pole.

Orbit Polar/Circular		Contact Time minutes		% of Orbit	
Orbit Alt.	Orbit Period	crater center	Mt. Malapert	crater	Mt. Malapert
50 km	1.88 hours	3 - 4	8 - 11	3	9

150 km	2.05 hours	6 – 9	15 - 19	6	14
300 km	2.3 hours	11 - 16	23 – 27	10	19
7000 km	20.4 hours	400	550	33	45
Molniya					
3344 km	4 hours	85	120	34	48
6233 km	8 hours	285	345	60	72
9058 km	12 hours	500	580	69	80

D. Earth Orbiting Relays

A single Earth orbiting relay, in a sufficiently high orbit such as GEO, HEO, or Molniya type orbits has line of sight to the near side of the Moon almost constantly. For example a relay in a GEO orbit has near side access 97% of the time. They will also allow periodic access slightly beyond the limb. Some link performance enhancements could be obtained, due to a lack of atmospheric distortion.

The cost to benefit ratio is very high for this option. The expense required to exceed the performance of existing terrestrial networks such as the DSN, would require at lest two relays and large diameter high gain antennae. The expense may be justified if the relays were design to enhance the capacity of the DSN for solar system missions. Existing assets such as TDRS could be used for lunar communications – but they are designed for Earth orbiting satellites thus have limitations in applicability.

IV. Surface Relay Options

Three surface relay options are considered in the trade space. The underlying assumption is that a rover unit inside a crater will not have line of sight to the Earth, and also will not have line of sight to an orbiting relay satellite for any significant periods of time. Therefore, a surface relay unit is necessary to transmit rover data to Earth. The surface relay options are summarized in Figure 5.

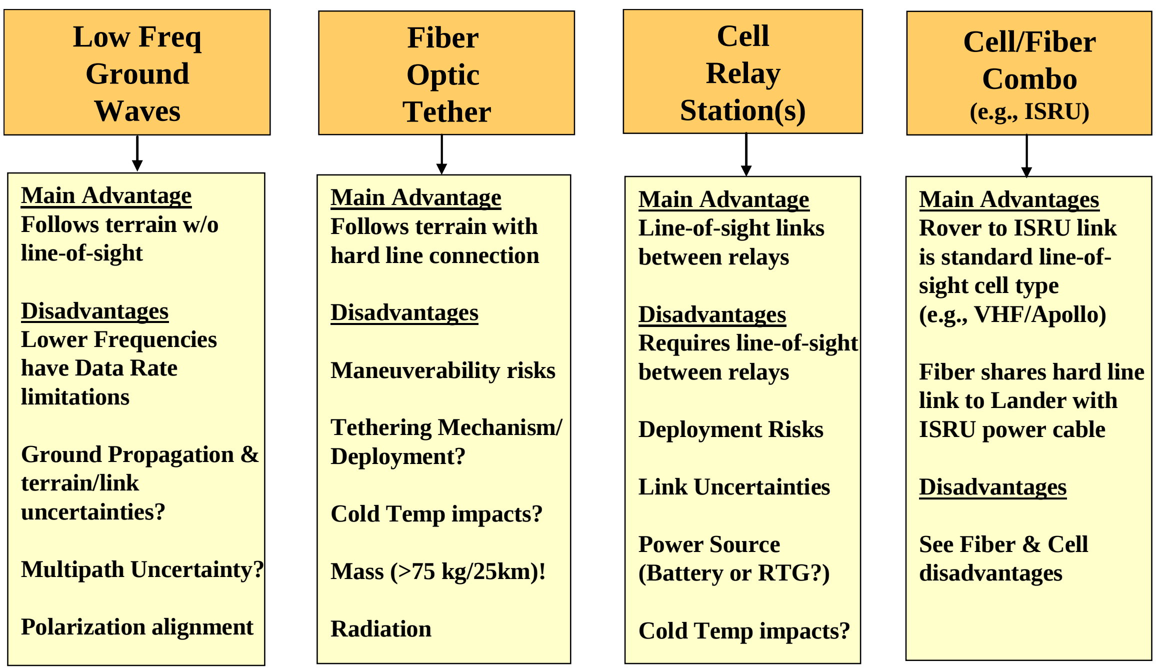

Figure 5. Lunar surface relay options and their main advantages and disadvantages.

A. Low Frequency Ground Waves

Low frequency ground waves are similar to Terrestrial radio wave communications. These waves can follow certain terrain features without line of sight. The advantage is that this is the smallest mass and volume communications package that can be placed on a rover or a lander, as it has been extensively developed and improved for Terrestrial applications. The two main disadvantages is the low data rate associated with low frequency waves, and surface properties of the terrain are highly uncertain. The electrostatic properties of lunar regolith may interfere with surface transmission by producing excess signal absorption and cutting down transmission range, or the crater rims may have sufficient vertical profile to prevent transmission along the crater slope. Multipath uncertainties and polarization issues also exist on the lunar surface. It may be desirable to carry a secondary experimental ground wave communications package to learn more about the electrical properties of the soil in the South Pole region.

B. Fiber optic tether

Using a fiber optic tether grants an advantage in that it can follow terrain with a hard line connecting points of communication. The data capacity of a fiber optic tether is the largest of all the options, and would provide a considerable infrastructure advantage. In some cases, power transmission along the same cable can be achieved to solve rover lunar night survival problems. However, the primary drawback of the fiber optic tether is the huge uncertainty of its operation in the lunar environment. Terrestrial optic fibers do not operate well below freezing, as the fibers become too brittle. Hazards such as line snagging and breaking also increase the maneuverability risk associated with a fiber tether. Finally, since crater floors are usually many km from the edge, a fiber optic tether would have a very large mass. Typical terrestrial optical fibers weigh around 100 kg/km. A 10 km fiber tether would weigh 1000 kg.

C. Cell Relay

A cell phone relay system could be placed on the lunar surface. The high frequency (VHF of UHF) of the relays would increase data transmission rates over ground waves, and many cell stations can be placed for coverage and redundancy. A lunar cell relay infrastructure can be envisions to enable communication over all terrains. The main disadvantage of this option is the placement of the cell towers or relay pods: they must be landed, transported on the surface, and deployed. Operation and survival of components must operate during the lunar night or permanent darkness are also unresolved issues.

D. Cell/Fiber Combination

A more robust option is a combination of cell towers and fiber optics tethers. Redundancy in the capabilities reduce the risk of communications failure. However, problems with development and deployment are unchanged.

	GW	FO	Cell	Comb	Pol	Mol
Total	**14**	**13**	**14**	**13**	**15**	**20**
COST	5	3	3	3	4	2
RISK	2	2	2	1	5	5
DATA VOLUME	2	4	3	3	3	4
AVAILABILITY	3	5	3	4	2	4
EXTENSIBILITY	2	1	3	2	1	5

Figure 6. Resulting score for various lunar communications options.

V. Lunar South Pole Communication Configuration

There are six lunar South Pole communications trade options that we evaluated using the evaluation table given in Figure 2. The six options are:

- Low Frequency Ground Waves (GW)
- Fiber Optics Tether (FO)
- Cell relay station (Cell)
- Cell/Fiber optics combination (Comb)

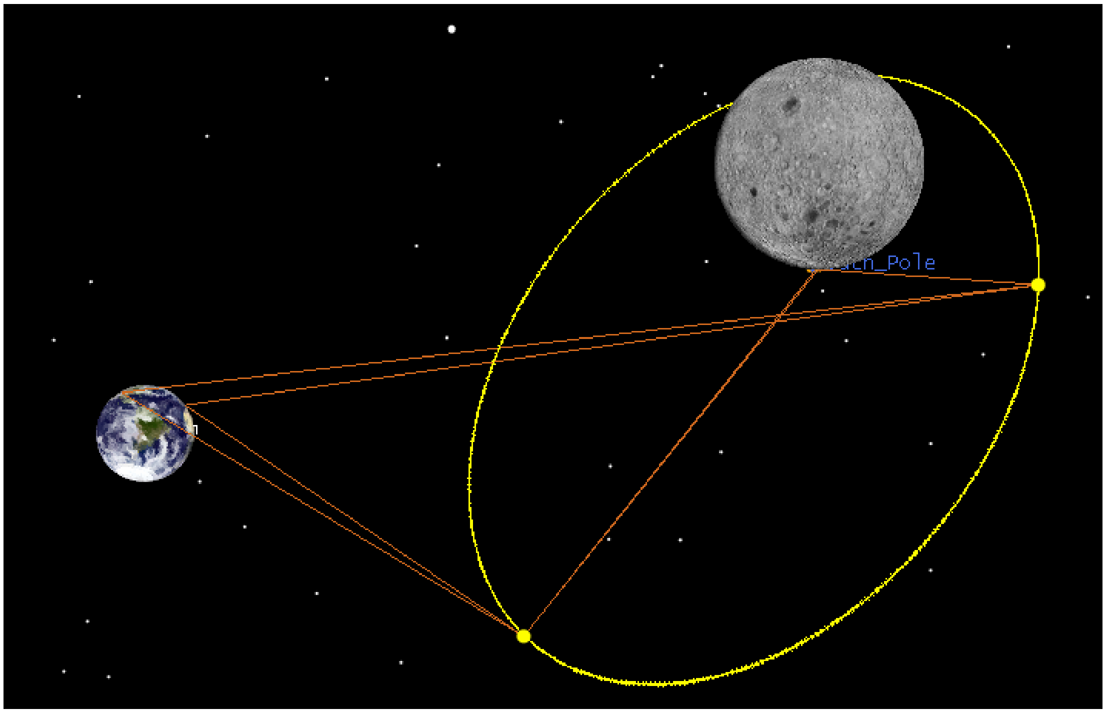

Figure 7. View of Two Relay Satellites in Molniya Orbit over the South Pole of the Moon. *Shown are links from the South Pole to the Relay Satellites and to the Goldstone and Madrid Stations of the DSN.*

- Relay Satellite in Polar Orbit (Pol)
- Relay Satellite in Molniya Orbit (Mol)

Figure 6 indicates the score for each of the six options. The option with the highest score is placing a relay satellite in Molniya orbit. It has very low risk, high data volume return, high command and control availability, and is very extensible to future missions. One or two relay satellites in Molniya orbit is a good start to a lunar communications infrastructure, both surface to surface, and surface to Earth links are well served.

As an example, the following Molniya orbit would be ideal for lunar communications. With orbital inclination of 53.1°, periselene altitude of 300 km, period of 12 hours, and an argument of periselene of 90°, one could obtain coverage of about 66% near the bottom of the southern edge of de Gerlache Crater for a single relay spacecraft. This orbit does not require maintenance ΔV, unless it is part of multi satellite constellation. This would be about 7 hours and 52 minutes every 12 hours. (Assumes a location of 87.3° South, 87.1° West, a depth of 3 km, diameter of 32.4 km, and a maximum slope of 25°.) At the center of the crater, coverage would be about 77% or 9 hours and 15 minutes per 12 hour orbit. This would likely be adequate for most reconnaissance or resource utilization missions. This orbit is shown in Figure 7, along with lines connecting to Earth and the South Pole.

VI. Conclusion and Recommended Solution

In support of LPRP rover missions at the southern polar region, it is our recommendation that a low cost communications relay should be launched prior to or with the LPRP rover, to a Molniya type orbit over the South Pole of the Moon. Subsequent landed LPRP missions would be able to use this asset to communicate with Earth. A second satellite will provide continuous relay and may eventually act as a replacement to the first. In the months prior to the crewed missions, high capacity communications relays may be added to the constellation, providing capacity for over 18 hours a day of high speed video imagery.

Acknowledgments

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References

[1]Neuner, G. E., “Lunar Communication Satellites,” *AIAA Communication Satellites Systems Conference*, AIAA, Washington, DC, 1966.

[2]Folta, D., and Quinn, D., “Lunar Frozen Orbits”, *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, AIAA, Washington, D.C., 2006.

[3]Farquhar, R. W., “Lunar Communications with Libration-Point Satellites,” *Journal of Spacecraft and Rockets 1967*, Vol. 4, No. 10, 1967, pp. 1383-1384.