THE EARTH BASED GROUND STATIONS ELEMENT OF THE LUNAR PROGRAM

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Abstract

The Lunar Architecture Team (LAT) is responsible for developing a concept for building and supporting a lunar outpost with several exploration capabilities such as rovers, colonization, and observatories. The lunar outpost is planned to be located at the Moon's South Pole. The LAT Communications and Navigation Team (C&N) is responsible for defining the network infrastructure to support the lunar outpost. The following elements are needed to support lunar outpost activities:

- A Lunar surface network based on industry standard wireless 802.xx protocols
- Relay satellites positioned 180 degrees apart to provide South Pole coverage for the half of the lunar 28-day orbit that is obscured from Earth view
- Earth-based ground stations deployed at geographical locations 120 degrees apart.

This paper will focus on the Earth ground stations of the lunar architecture. Two types of ground station networks are discussed. One provides Direct to Earth (DTE) support to lunar users using Ka-band 23/26Giga-Hertz (GHz) communication frequencies. The second supports the Lunar Relay Satellite (LRS) that will be using Ka-band 40/37GHz (Q-band).

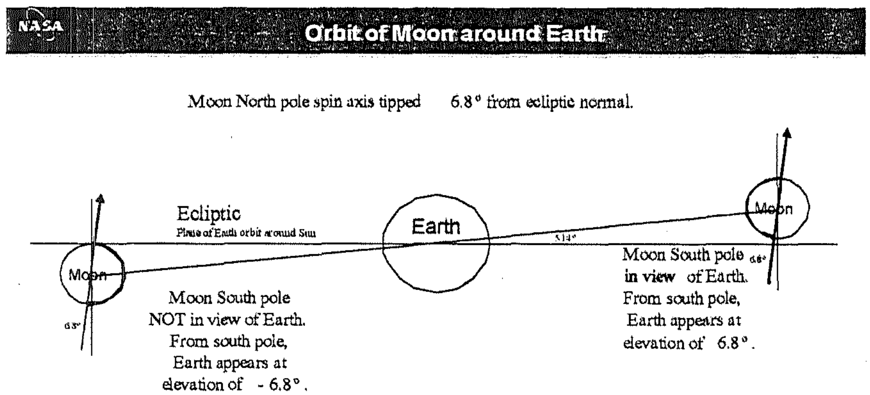
This paper will discuss strategies to provide a robust operational network in support of various lunar missions and trades of building new antennas at non-NASA facilities, to improve coverage and provide site diversification for handling rain attenuation.

1. Introduction

The Moon's South Pole is a leading candidate for establishing a human outpost. The lunar poles provide several advantages compared to other areas of the lunar surface, such as a relatively stable thermal (temperature) environment, sunlight more than 80% of the time at "Points of Eternal Light", as well as the possibility of ice.

Several studies by the National Aeronautics and Space Administration (NASA), as well as other countries, have been done over the past several years to explore the best options for communicating from the Earth with the initial lunar Landers, then later expanding this communications network as exploration increases. In the coming decades, this communications network for lunar and Mars outposts is expected to expand to include higher bandwidths, different types of protocols and frequencies, different classes of data, and the challenge of coverage during the lunar to Earth direct line-of-sight blackout periods.

"It's tricky at the poles because the Moon's axis is tilted about 5 degrees off the Earth-Moon line. So if you're at the pole, Earth is sometimes 5 degrees above the horizon, which is good. But sometimes it's 5 degrees below the horizon. Then you have a communications blackout. Periods of no communication would last a bit less than 2 weeks." [Philip Stooke, a space scientist at the Departments of Geography and Physics and Astronomy at the University of Western Ontario in London, Ontario, Canada [1] (see Figure 1)].



Earth will be at least 1°above horizon for about 12 days out of an approximate 28-day cycle

Figure 1 - Earth View of Lunar South Pole

To provide South Pole coverage during outage periods of 2 weeks or to support robots in craters without a view of the Earth, Lunar Relays are required. The orbit of these lunar communication satellites is being studied. The standard lunar equatorial orbit may not be the best solution, since halo orbits can provide a continuous view of the Earth and the far side of the lunar surface. The leading candidate orbit for lunar South Pole coverage is a 12-hour stable (frozen) orbit shown in Figure 2. This orbit is biased towards one pole and provides 65% coverage of the South Pole using one lunar relay. To provide 100% coverage, two lunar relays are needed. The lunar orbit also poses a three-body gravitational field of two dominant mass bodies upon a very small third mass, the communication satellite, which exerts a negligible gravitational field. These gravitational effects have to be taken into account and present an additional challenge for providing continuous communications. These relay satellites require a "trunk line" to relay the data back to Earth. To prevent radio frequency interference (RFI), trunk lines use different frequencies than those assigned to the user. The remaining sections of this paper deal with building a new ground network infrastructure to support the Explorations Program.

The topics will include:

- Maximizing use of existing NASA sites
- Coverage and availability of existing sites
- New spectrum restrictions on use of Ku-band and X-band, requiring use of Ka-band
- Mitigation strategies for dealing with rain

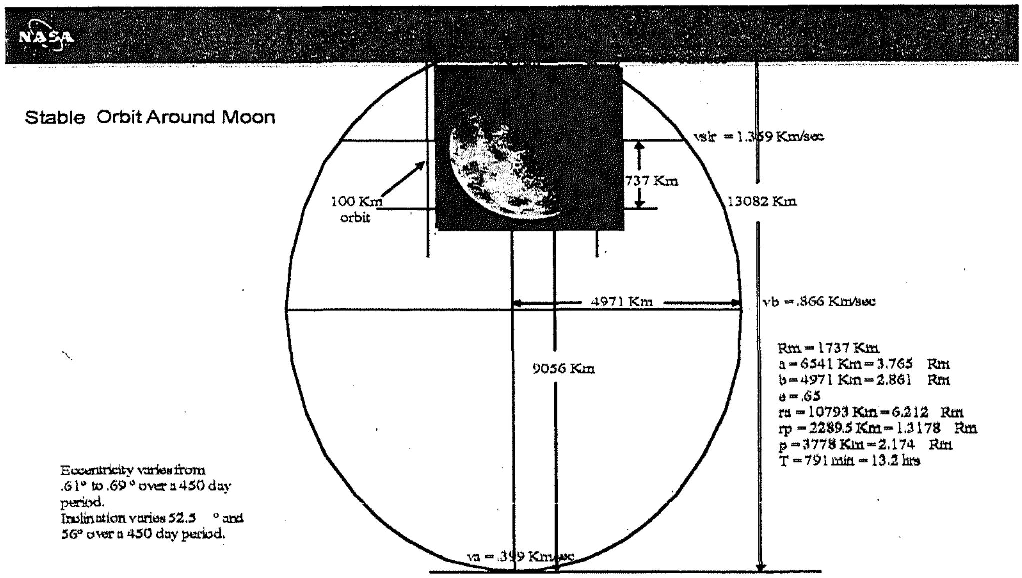


Figure 2 - Proposed Relay Orbit

2. Direct To Earth (DTE) Network

NASA will upgrade the communications network infrastructure to support missions for the manned lunar exploration in the 21st century. Earth-based direct communications support spacecrafts in transit and the lunar base when in view. Besides basic communications, higher data rates will be required, particularly for the manned lunar missions, including any lunar outposts. The current NASA plan is to increase the data rate to at least the 150 megabits per second (mbps) range using the Ka-band 26 GHz frequency. The Deep Space Network (DSN) is adding Ka-band 26 GHz to its 34-meter network in support of the James Webb Space Telescope (JWST). The Lunar Reconnaissance Orbiter (LRO) and Solar Dynamics Observatory (SDO) are constructing a Ka-band 26 GHz 18-meter antenna at the White Sands, NM facility. By 2014, two additional TDRSS (Tracking and Data Relay Satellite System) satellites (K and L) will be deployed to support the Crew Exploration Vehicle (CEV) mission to the International Space Station(ISS) using the Ka-band 26 GHz.

The first lunar outpost phase supports short duration missions. The plan calls for two missions per year. Short-stay missions will take place at the lunar vicinity, beyond the coverage of TDRSS. The primary method of supporting communications will be using Earth-based ground stations (DTE). These missions will be 7 days in duration and can be planned for periods of ground communications coverage of the Moon's South Pole to avoid the communication blockage periods between the lunar surface and the Earth.

NASA would like to maximize use of existing NASA sites and infrastructure. The most cost-effective choice to support short-stay missions is to use existing DSN sites [2]. Existing 34-meter Beam Wave Guide antennas will be upgraded with Ka-band 23 to 26 GHz and an S-band TDRSS compatible signal. The LRO 18-meter antenna, referred to as White Sands 1 (WS-1), will also be used for these missions. Once the frequency of the lunar missions is increased, 18-meter antennas will be deployed at DSN sites in Madrid, Spain and Canberra, Australia and, together with WS-1, will provide the lunar DTE network. The 18-meter antenna is used as a baseline for users to close their link margins. Rain attenuation for DTE will be provided by using the 34-meter as backup (additional 10 decibels compared to 18 meter) or by using S-band. An issue with the proposed approach is that the WS-1 DSN sites, as shown in Figure 3, provide 98.5% coverage of the Moon.

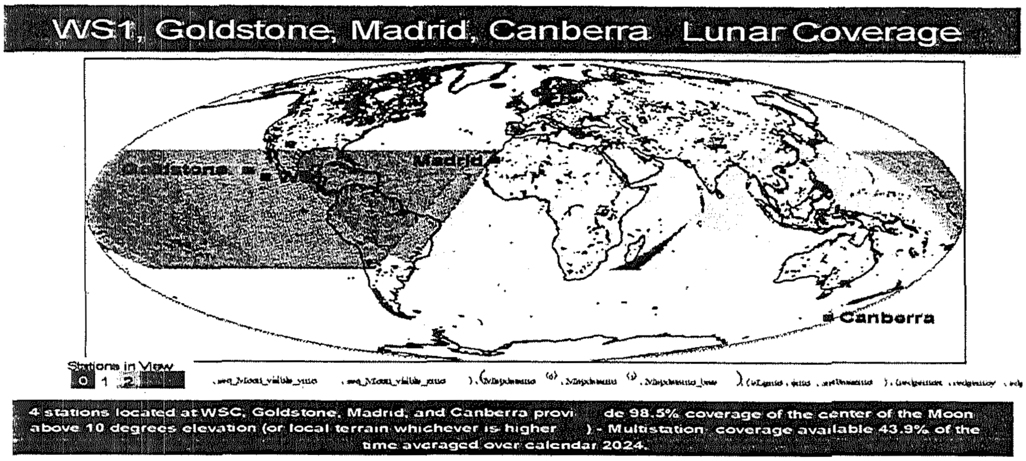


Figure 3 - DSN/ WS-1 Coverage

3. The Lunar Network Architecture and Availability

The lunar outpost should be supported with a combination of Earth-based antennas, relay satellites, and lunar surface communication assets. The lunar surface network will be built around a commercially available standard, such as 802.xx. The hub of the surface network is the Lunar Communication Tower (LCT) which serves as a gateway and communicates directly to the LRS. The LCT data rate is planned to be 200 Mbps. In addition to transferring LCT data to Earth, LRS provides rovers with *in-situ* navigation and voice. The architecture is depicted in Figure 4.

The availability of services to users is a combination of the three elements: LCT, LRS, and relay ground stations. The LCT availability is rather high at 99.5% due to the need to be self-contained on the surface with built-in redundancy and failovers. Each relay satellite's availability is 97%, from which 2.5% is allocated for housekeeping activities such as orbit maintenance, momentum dumps, and a spacecraft flipping maneuver that is required periodically to stay aligned with the Sun, Moon, and Earth. This fourth ground station increases the availability of the LRS element from 97% to 99.5%, thus significantly improving the overall availability of the lunar network.

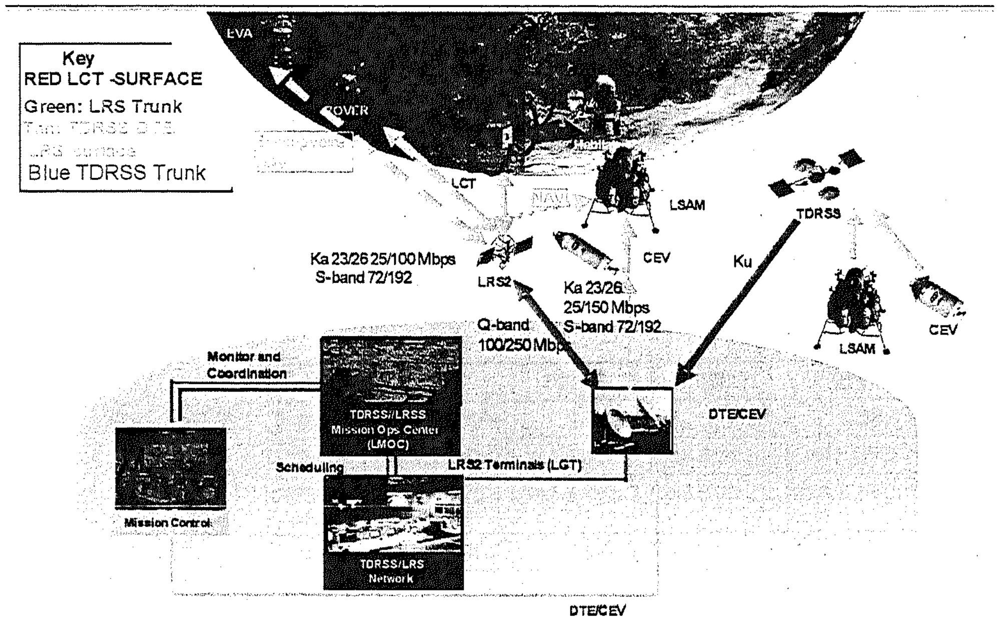


Figure 4 - Lunar Communication Architecture

4. Relay Ground Stations

The dedicated LRS ground stations provide a challenge in achieving high availability. The combination of geographical coverage, station downtime for maintenance, and rain attenuation, degrades the ground antenna availability to 90%. Unlike DTE, the LRS ground stations have no "elegant" options dealing with rain diversity.

- Unlike the Ka-band 26 GHz that is shared by other non-lunar missions, the Ka-band 37/40 GHz (Q-band) 18-meter antennas are dedicated to lunar relay satellites.
- LRS is required to use the same S-band frequency as its users. The LRS will need to shut down the S-band transmitter while serving its users. Use of X-band for LRS would alleviate this problem.
- Q-band is very susceptible to rain.

There are two approaches to address the rain diversification problem; one is by reducing users' data rates and the other is to build more ground sites. Providing a high availability service with three planned ground stations requires a strategy of increasing the gain by reducing the data rates. For example, the Q-band for Canberra indicates that a gain of 3 dB can be achieved by reducing the data rate by half and will improve weather performance from 95% to 97.5% availability.

To provide 100% geographical coverage of the Moon and diversification to handle rain requires the use of six sites identified in the Exploration ground antenna study [3]. The proposed approach is to have two sites in each geographical zone. These six proposed sites are listed below, namely:

- US: Goldstone and White Sands
- Africa/Europe: Madrid and Hartebeesthoek, South Africa
- Australia: Canberra and Dongara

The six site approach is rather expensive as it requires building antennas at two non-US sites. The use will only be 16% since they cannot be shared by other users unless they are upgraded to support multiple frequencies. Analyzing the coverage of the six sites shows that the system exceeds the requirement for double coverage and provides triple and even quadruple coverage in some areas.

5. LRS FOURTH SITE

As discussed earlier, the minimum number of sites required to support LRS is four and this increases the LRS availability from 97% to 99.5%. Three sites are needed to move users' data back to Earth and the fourth LRS site is used as overflow to perform spacecraft housekeeping for overflow dumping for the LRS recorder. The LAT recommended Goldstone (GDS) as the fourth site since deploying antennas at an existing US site is the most cost-effective. Goldstone and White Sands provide geographical diversification to handle rain attenuation of the US zone. However, GDS adds only 13% of double coverage area since the GDS coverage area overlaps with White Sands and Madrid. The total ground station system only has double coverage for half of the time and an outage in Canberra will significantly impact the total system. The proposed approach for deploying DTE and Relay antenna is shown in Figure 5.

			2018	2019	2020	2021	2022	
USA	WSC	18m *	LRS2	LRS2	LRS2	LRS2	LRS2	Q-band
	WSC	18m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM	Ka-26/23
	Goldstone	34m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM	Ka-26/23 Backup
	Goldstone	18m *				LRS3	LRS3	Q-band
Australia	Canberra	18m *	LRS2	LRS2	LRS2	LRS2	LRS2	Q-band
	Canberra	18m *		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM	Ka-26/23
	Canberra	34m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM	Ka-26/23 Backup
Europe	Madrid	18m *	LRS2	LRS2	LRS2	LRS2	LRS2	Q-band
	Madrid	18m *		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM	Ka-26/23
	Madrid	34m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM	Ka-26/23 Backup

* New Antenna

Figure 5 – Proposed Deployment

Hartebeesthoek (or Dongara) as an alternative, non-NASA, fourth site would increase the overall double coverage area to over 80%. Another consideration in selecting this site would be the International Telecommunication Union (ITU) rain and weather attenuation information in Figure 6. Based on ITU, GDS and Dongara require less 3 dB than Hartebeesthoek to close the link.

Site	Availability / Frequency	95%	97%	99%
WSC 32N : 106W	Ka 26 Ka 37.5	2.0 / 3.61 3.8 / 5.5	2.9 / 4.65 5.4 / 7.15	6.0 / 7.83 11 / 12.81
GDS 36N : 116W	Ka 26 Ka 37./5	0.5 / 1.7 1.0 / 2.4	0.7 / 1.94 1.5 / 2.86	1.6 / 2.82 3.1 / 4.5
Canberra 35S : 148E	Ka 26 Ka 37.5	1.5 / 3.3 2.8 / 4.76	2.1 / 4.01 4.1 / 6.03	4.5 / 6.05 8.3 / 10.41
Dongara 29.5S : 114.93E	Ka 26 Ka 37.5	1.2 / 3.05 2.4 / 4.03	1.8 / 3.57 3.4 / 6.48	3.8 / 5.31 7.1 / 14.07
Madrid 40N : 4.2W	Ka 26 Ka 37.5	0.8 / 2.47 1.5 / 3.33	1.1 / 2.85 2.2 / 4.03	2.4 / 4.21 4.6 / 6.49
HBK 29S : 30E	Ka 26 Ka 37.5	2.5 / 5.43 5.31 / 7.56	3.65 / 6.74 7.3 / 9.58	7.4 / 11.23 15.04 / 17.29

dB to close link 10% elevation

Figure 6 – ITU Rain Fade

6. Summary

Building ground antennas for the lunar program is a challenging task. Since we are dealing with human nature, it is tempting to over-engineer and build multiple antennas at multiple sites. It has been demonstrated that with some innovation, paying attention to operations concepts, and using existing DSN capabilities as backup to the lunar communication ground network, a robust capability can be provided.

Realizing that four sites are necessary for LRS, a more detailed analysis will be done in selecting a fourth site. Tools such as Satellite Tool Kit and rain models can further enhance the decision on where to build the fourth ground station to improve availability.

The current Lunar Architecture Team recommendations for the antennas shown in Figure 7 are described below:

- For DTE communications, two new 18-meter antennas at Madrid and Canberra will, together with White Sands, become the complete DTE network. DTE will be backed by an existing DSN 34-meter antenna supporting Ka-band 26 GHz.
- As an option to DTE, DSN might decide to provide DTE, as part of its new array infrastructure

LRS antenna activities are:

- Deploy Q-band (Ka-band 37/40 GHz) 18-meter antennas at four existing DSN and White Sands sites, three for users and one site as LRS overflow
- Conduct a fourth site trade between Goldstone and non-NASA site

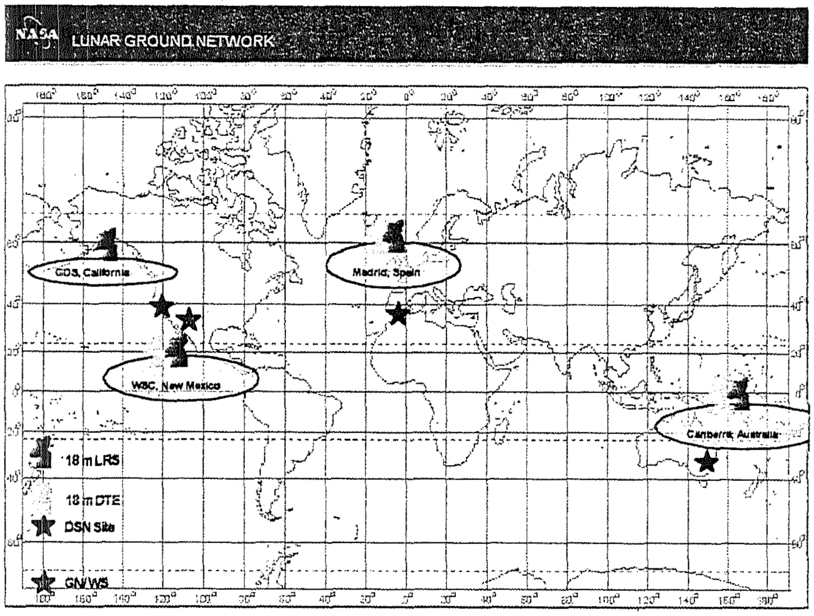


Figure 7 – Lunar Antenna Locations

7. References

[1] Leonard David, Lunar South Pole Landing Sites Studied, *Space News*, June 2003

[2] Charles H. Lee, California State University, Fullerton, Kar-Ming Cheung, NASA Jet Propulsion Laboratory, USA, Deep Space Network and Lunar Network Communication Coverage of the Moon IAC-06- B3.4.01, October 2006

[3] Robert J. Wallace, Dick Emerson JPL, Jean Patterson, Jonathan Gal-Edd, GSFC, et al., Exploration Communications and Navigation Systems (ECANS), Lunar Ground System Study Preliminary Report, October 2006

[4] The Space Communications Architecture Working Group (SCAWG) report of NASA Space Communications and Navigation Architecture Recommendations for 2005-2030, October 2006