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Lunar Ground Station Comparison between Optical and RF Systems

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ABSTRACT

This paper points out the lack of existing ground infrastructure that will be needed to communicate with the upcoming lunar missions. It discusses basic considerations about site locations and the pros and cons between Radio Frequency and laser-based communications. It also points out the challenges and risks that industry needs to consider for building this infrastructure. Finally, it recommends a hybrid solution for the future.

Keywords: Lunar communication, lunar sites, RF-requirements, ground stations, hybrid network

1. INTRODUCTION

This year 50 years have passed since the last humans landed on the Moon. Now, the Moon is back in the spotlight for human space exploration in the context of eventually going to Mars. In preparation for the human phase many unmanned missions are planned. These missions are especially important since the new focus is on the far side of the Moon and the poles where water has been identified. Only with water available will it make sense to have continuous human presence on the Moon and eventually use it as a steppingstone to Mars.

The present lunar mission manifest contains at least 140 planned missions to the Moon before the end of this decade and all of them need to communicate with Earth, in some cases via Relay Satellites.

While microelectronics has developed in a breath-taking speed during the last five decades the basic physics remain the same. Rockets need the same thrust to reach lunar orbits and ground station antennas need the same gain and therefore size for closing the communication link as 50 years ago.

Only few unmanned missions have been conducted to the Moon during the last decades and they were usually supported by expensive Agency owned Deep Space Antenna Networks (DSN) that were designed for much longer distances. Except for DSN, only few antennas exist that can support lunar communication links today. Most of them are leftovers from the Apollo time, transformed old C-band antennas from the former Intelsat Communications network or large old LEO (Low Earth Orbit) antennas.

Therefore, new communication infrastructure is needed to allow all missions to communicate between Moon and Earth. This deficit has barely been addressed and it has somehow been assumed that the infrastructure either exists or that industry quickly fills the void as it has happened for LEO NewSpace (KSAT^{Lite}). Given that purchasing a lunar size antenna has a lead time of at least two years such infrastructure cannot be made available on short notice even if funding is there.

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1.1 Baseline requirements for Lunar communications

The focus to the lunar poles presents additional challenges since they cannot be always reached under longer periods with direct to Earth (DTE) antennas. Lunar relay satellites will be needed to complement communications with, since the poles are not accessible through DTE. Obviously, the far side communication will be fully reliant on lunar relay satellites. For far side communications a halo orbit around L^2, which is behind the Moon results in almost continuous communication capabilities. The Chinese Queqiao[1] relay satellite is an example of a satellite in such an orbit.

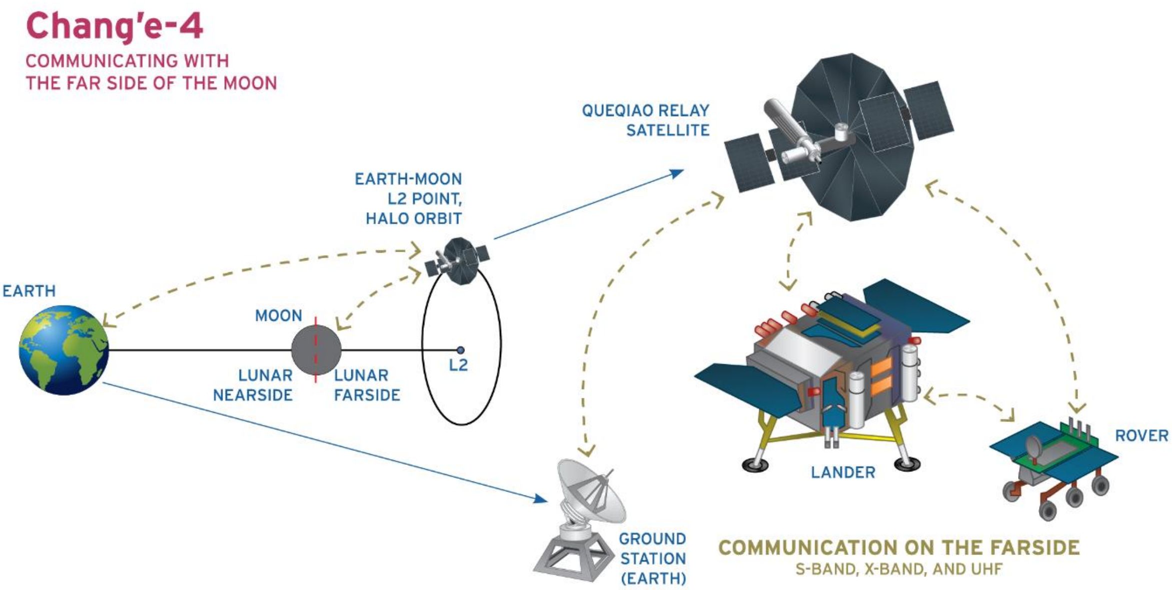

Figure 1. Communications with the far side of the Moon

Since Low Lunar Orbits (LLO) are unstable[2] only lunar relay satellites in an elliptical frozen orbit can also achieve communications with the far side and more importantly with the poles of the Moon. As polar locations are key to long term lunar presence all upcoming relay missions have chosen this solution. The 86º lunar frozen orbit provides the best visibility of the poles, but a constellation of such satellites, ideally with intersatellite links, will be needed to achieve continuous polar coverage.

Due to the necessity of lunar relay satellites several projects are ongoing to establish such a capability. The Lunar Pathfinder satellite by SSTL is the first in line with a planned launch date in early 2025. Lunar Pathfinder is also seen as the first satellite in the Lunar Communications and Navigation Services (LCNS) constellation planned by ESA.

All relay satellites need to bring back the communication to Earth and have roughly the same requirements as any other spacecraft using DTE for a successful Lunar Earth link. Therefore, the establishment of a lunar focused antenna network is even more important. As an alternative the communication link can also be realized through an optical laser link using a telescope. The two alternatives are discussed here.

1.2 Considerations for locations of Lunar Antennas and Telescopes

Since lunar dedicated ground infrastructure does not exist today, we have the freedom to place it at the best locations minimizing the number of stations needed and guaranteeing continuous lunar coverage. In summary one needs minimum three stations spread evenly around the globe within +/- 35º latitude of the equator. Independent of ground station location the poles of the moon cannot be accessed during longer periods.

1 https://en.wikipedia.org/wiki/Queqiao_relay_satellite
2 https://arc.aiaa.org/doi/abs/10.2514/2.5064?journalCode=jgcd

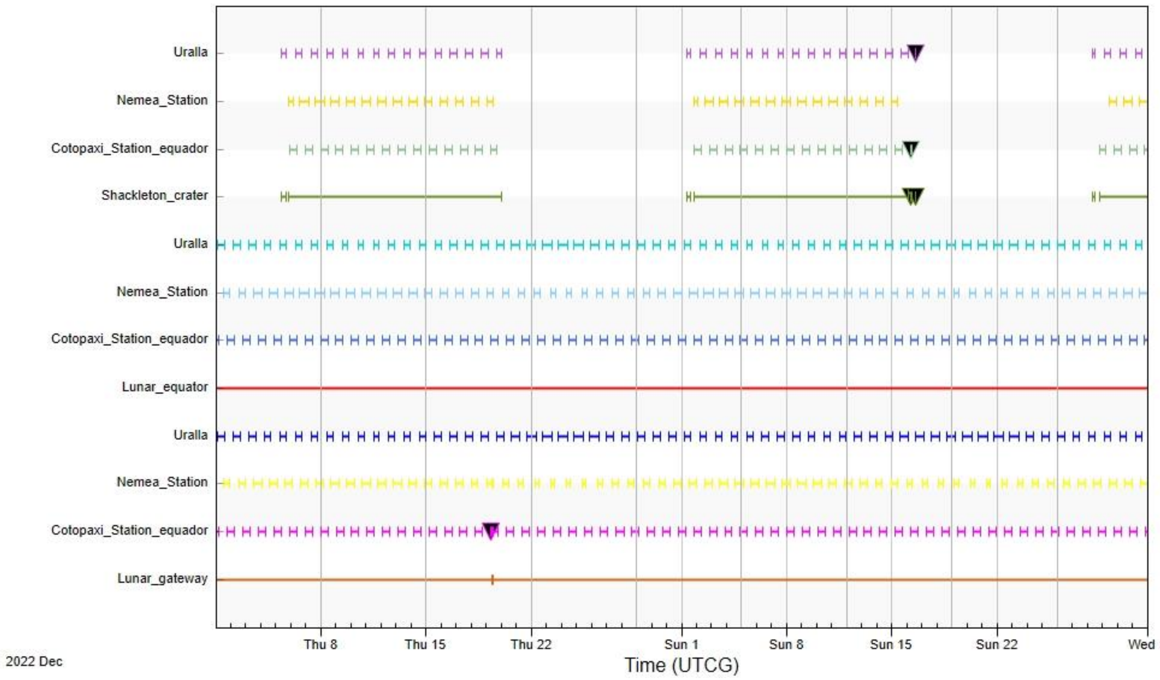

Figure 2. Access to lunar poles, gateway and equator[3].

The STK plot in Figure 2 shows a combination of three stations with roughly 120º spacing and locations in Uralla (Australia), Nemea (Greece), and Cotopaxi (Ecuador). This combination allows for a continuous communication to the lunar equator (red line) and almost continuous communication to the lunar gateway (brown line). It also shows that the Shackelton Crater cannot be reached with any DTE combination for almost two weeks at a time – relay satellites are the only way to assure communication then. The same three ground stations will give almost continuous coverage during the period when a DTE link can be established to the crater.

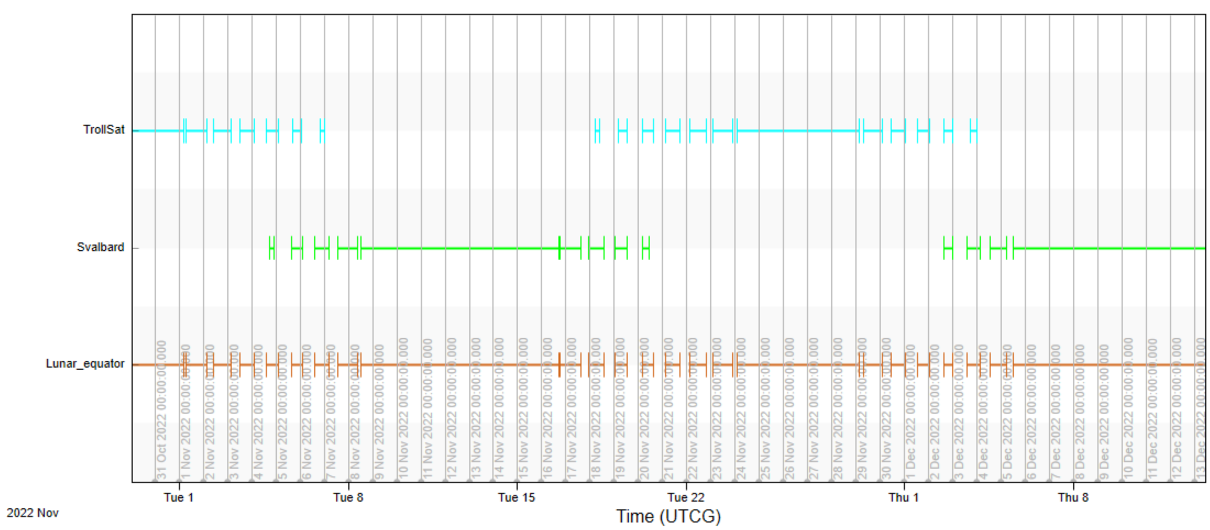

Figure 3. Lunar coverage from polar stations[3].

3 STK Analysis performed by OHB Sweden

KSAT is a specialist on polar communications and the largest stations are located close to the poles to maximize the coverage for LEO satellites. When polar locations are used for Lunar operations, an interesting picture emerges. The STK analysis in Figure 3 shows the combination of KSAT's main polar sites. The stations (TrollSat 72ºS and SvalSat 78ºN) augment each other almost perfectly. Another advantage of a polar combination that other sites cannot provide is constant lunar visibility for up to one week. The lunar coverage achieved is over 90 %.

This basic coverage analysis applies both for RF and optical communication, but in the case of optical more locations are needed to reduce the likelihood of unavailability due to atmospheric attenuation.

2. RADIO FREQUENCY AND LASER BASED LUNAR COMMUNICATIONS

There are two main ways to solve the communication between Earth and CIS-Lunar Spacecraft. One is by communicating in the wavelength of Radio Frequencies (RF), typically in S-band, X-band, or Ka-band. The second is by communicating in optical frequencies, typically at 1550 nm (optical C-band).

2.1 Lunar RF-communications

Communication in RF is highly operational, automated, and weather independent. KSAT provides more than 2000 RF-links per day between LEO Spacecraft and the ground. It is expected that in the year 2023 more than one million passes will be supported by KSAT, hence the RF communication link for LEO has been commoditized.

The frequencies to be used for Lunar communications have been agreed in the Interagency Operations Advisory Group (IOAG) and more specifically by the Lunar Communications Architecture Working Group (LCAWG). Based on this NASA and ESA have agreed on LunaNet[4] (Lunar Network), which provides a minimum description of services and interfaces with the aim to provide a baseline for interoperability[5]. One part of LunaNet is its Interoperability Frequency Plan which is the guideline for the RF-antennas that need to be established for Lunar direct to Earth communications (DTE).

Following the LEGS (Lunar Exploration Ground Sites) requirements in Table 1, the antennas needed will have an approximate size of 20 meters and a triband feed for S-, X- and Ka-band up- and downlink. Depending on the location of the antenna a radome may be needed to make sure the Ka-band link is not disturbed by wind or precipitation. A rough calculation shows that an investment of 15 MUSD per antenna is needed to fulfill these requirements, including site establishment.

As one single Mission with the requirement to have continuous contact to the Moon can utilize the entire lunar visibility capacity of the three lunar antennas (assuming a single RF-link at a time), industry must propose a way to distribute the lunar link between multiple missions to keep the communication cost down.

4 https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability
5 https://esc.gsfc.nasa.gov/static-files/Draft%20LunaNet%20Interoperability%20Specification%20Final.pdf

Table 1. LEGS radio frequencies and performance[6]

Antenna System Radio Frequency Operating Regimes

Radio Frequency (RF) Band	Operating Frequency	
	Lower limit	Upper limit
S-Band (Forward)	2025 MHz	2120MHz
S-Band (Return)	2200 MHz	2300 MHz
X-Band (Forward)	7145 MHz	7235 MHz
X-Band (Return)	8400 MHz	8500 MHz
Ka-Band (Forward)	22.55 GHz	23.15 GHz
Ka-Band (Return)	25.50 GHz	27.0 GHz

RF Performance Criterion	Radio Frequency Performance (Forward)		
	S-Band	X-Band	Ka-Band
EIRP (minimum) [3]	81 dBW	86 dBW	89 dBW
Approx 3 dB Beamwidth[3]	0.5°	0.1°	0.04°
Forward Distortions [2]	1 dB max	1 dB max	1 dB max
Carrier Modulation	Direct PCM/PM PCM/PM/PSK, OQPSK, BPSK[1]	Direct PCM/PM PCM/PM/PSK, OQPSK, BPSK[1]	BPSK, OQPSK Filtered OQPSK[1]
Max Data Rate	10 Msps	10 Msps	40 Msps

2.2 Lunar Optical Communications

The importance and effectiveness of optical communications between spacecraft is clear. One can expect that most inter-satellite links will be based on optical communications in the future. Afterall, they offer higher throughput, lighter mass, and less problems with interference.

Free Space Optical (FSO) Communication between Earth and spacecraft is always confronted with the challenge of the atmosphere causing attenuation and leading to higher bit error ratios. Water, smog, scintillation add to the challenges of beam dispersion and general atmospheric absorption. High pointing accuracy both from the telescope on earth and on the spacecraft require high precision on both ends to establish a stable link. Impact of weather means that no guarantees can be given and that more sites are needed to reduce the likelihood of losing data.

KSAT is part of an effort to achieve operational stability that allows FOS to compete with RF for LEO and hopefully lunar communication. Several things are challenging – first and foremost the lack of optical payloads flying and available for testing optical ground stations (OGS). Another focus area is integrating multiple telescopes into a network that can be addressed through a single network operations center (NOC). This is happening right now and four telescope are in the process of being integrated to the KSAT NOC. With these issues solved other operational challenges, especially the pointing accuracy, can be addressed. This network of optical stations is called the optical Nucleus network and is open to other telescopes that want to participate. The Nucleus network is presented in the poster session at this conference.

6 https://essp.larc.nasa.gov/EVI-6/pdf_files/LEGS%20Brochure%20r20.pdf

Figure 4. KSAT optical ground stations at Nemea, Greece. Part of the Nucleus Network.

Given the sensitivity of FOS to atmospheric conditions the present locations of all Nucleus stations are not ideal, except for the ESA OGS on Tenerife. At least five new sites on high altitude (to minimize the atmosphere) with dry and low wind conditions need to be established to enable an operational service that can compete with RF. The best location in KSAT's own network of 22 ground stations is TrollSat in Antarctica with minimal participation and clear skies at 1500 m elevation.

The Nucleus network can in principle also used for lunar communications, but for an operational scenario with high data speeds telescope diameters of 1 – 1.5 m would be desirable. The advantage of telescopes is that they are much more compact and therefore cheaper. A telescope optimized for lunar communication should cost in the order of 3-4 MUSD, including site preparation. This is approximately a quarter of a corresponding lunar RF antenna. This makes it feasible to support a larger number of sites (e.g. 6-8) around the globe adding inherent backup due to the overlap of visibility.

3. CHALLENGES AND RISKS

Like for LEO, ground station providers should take over the risk of investment in lunar ground communications infrastructure from the Space Agencies or large companies. They have the operational experience of steering many antennas remotely in an effective manner and operating multiple sites.

Mission delays are the biggest challenge since having idle aging infrastructure waiting for a single mission is a large financial risk. At the same time, the long lead time to establish this lunar infrastructure also puts missions in risk that assume that the infrastructure exists and is available and start to search for communication solutions too late.

Other risks are a sudden end to the Moon program (the last Lunar spell lasted only 5 years) or long-term delays (e.g. due to a mission failure). At the same time NewSpace has planted an expectation that things can be done much cheaper than before. This cannot apply here.

The investments required for the lunar ground infrastructure are of a magnitude the private actors in the ground station industry are not used to – most are small and medium enterprises. At the same time, these investments are almost negligible compared to the wider Moon program. Safe and redundant communications are a must and needed for risk reduction of all missions. But risks sharing between the mission owners and ground station industry that allows it to make these investments is still missing, which is delaying the establishment of this crucial infrastructure.

4. SUMMARY AND RECOMMENDATIONS

The communication link between Moon and Earth is heavily underserved and new infrastructure is needed to allow for safe lunar missions.

This brief comparison of RF and Optical communication to the Moon shows that RF is and will remain the classic safe option and will continue to be bedrock for all critical communication. At the same time optical communication offers potentially large financial savings and higher data rates. Once an operational stability has been achieved, an optical network of stations around the globe could augment the lunar RF backbone infrastructure and form a lunar hybrid network that offers a good mix of cheaper high-bandwidth communication and reliable RF-links for critical data.

To get closer to such a solution KSAT continues to build its hybrid network for LEO satellites, where the operational know how and internal developments can later be applied to the Moon. Further, more optical payloads both in LEO and CIS-Lunar are needed to gain operational experience for optical links and prove their usefulness and cost effectiveness for lunar communications.