SpaceOps Conferences
28 May - 1 June 2018, Marseille, France
2018 SpaceOps Conference

10.2514/6.2018-2612

Lunar Relay Coverage Analysis for RF and Optical Links

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This paper describes our effort in searching different lunar relay architectures and assessing their coverage performance and other pros and cons for RF and optical links. Regarding RF links, we considered three notional lunar relay architectures, all communicating with the three sites of the Deep Space Network (DSN): Goldstone, California; Canberra, Australia; and Madrid, Spain: 1) A constellation of three relay orbiters: two at the Polar frozen elliptical orbits, and one at an equatorial circular orbit. 2) One relay orbiter in a 74-day Lissajous orbit at Earth-Moon Lagrange Point L2. 3) One relay orbiter in a 14-day Lunar distance retrograde orbit. Regarding optical link, we considered a notional multi-hop relay architecture that consists of one relay orbiter in a 74-day Lissajous orbit at Earth-Moon L2 (as in architecture #2 in the RF case), three Near-Earth relay satellites in geosynchronous orbit at longitudes 187° E, 110° E, and 347° E, and three ground stations at White Sands (US), Guam (US), and Tenerife (Spain). We introduce the additional constraints of Sun-"Earth"-Probe (SEP) angle for return links, and Sun-Probe-"Earth" (SPE) angle for forward links. SPE and SPE angles determine the amount of sunlight (noise) that goes into the detector of the telescope, thus affecting the capacity of an optical link.

I. Introduction

DUE to the renewed interest in lunar exploration, both for scientific and economic reasons [1][2], many missions are planned to visit the moon from various countries in the next 10 years (see Table 1).

Table 1 Lunar Missions To be Launched During Decade 2018 - 2028

Mission	Launch Year	Agency	# of Vehicles	Mission Type
Chandrayaan-2	2018	ISRO	3	Orbiter/lander/rover
Chang'e 4	2018	CNSA	2	Farside Lander/rover
Chang'e 5	2019	CNSA	2	Orbiter/rover
Chang'e 6	2020	CNSA	2	Orbiter/rover
Korea Pathfinder Lunar Orbiter (KPLO)	2020	KARI	1	Orbiter
Korean Lunar Mission Phase 2	2020s	KARI	3	Orbiter/lander/rover
Luna-Glob	2019	Roscosmos	1	Lander
Luna Resurs-1 Orbiter	2022	Roscosmos	1	Orbiter
Luna Resurs-1 Lander	2023	Roscosmos	1	Lander
Luna-Grunt (Luna 28) Resurs-1	2020s	Roscosmos	1	Capsule
Smart Lander for Investigating Moon (SLIM)	2021	JAXA	1	Lander
Resource Prospector*	2020s	NASA	2	Lander/rover
Lunar Communications Pathfinder*	2020s	Goonhilly, SSTL, ESA	1	Relay Orbiter
Deep Space Gateway (DSG)*	2022-2026	NASA	4	Orbiter
International Lunar Exploration Precursor mission*	2024	ESA	3	Lander + Rover + Ascender
International Human Lunar Surface Architecture*	2028	ESA	3	Lander + Rover + Ascender
Exploration Mission-1 (EM-1)**	2019	NASA	1	Orbiter
Exploration Mission-2 (EM-2)**	2023	NASA	1	Orbiter
Lunar Flashlight	2019	NASA	1	CubeSat Orbiter
Lunar IceCube	2019	NASA	1	CubeSat Orbiter
Lunar H-Mapper	2019	NASA	1	CubeSat Orbiter
ArgoMoon	2019	ASI	1	CubeSat Orbiter
Omotenashi	2019	JAXA	1	CubeSat Lander
Equuleus	2019	JAXA	1	CubeSat Orbiter
SpaceIL	2019	Israel	1	CubeSat Orbiter

* Proposed mission or mission concept in planning.

** Not exactly a lunar mission; rendezvous to the Distant Retrograde Orbit (DRO)

In addition to orbiters, landers, and rovers, more sophisticated mission concepts that include sample return, establishment of a permanent lunar base, and the use of CubeSat/SmallSat for technology demonstrations are being considered. The anticipated build-up of lunar orbiting and surface assets warrant the need of a lunar relay infrastructure that provides communications and navigation services for long-term lunar exploration.

This paper describes our effort of searching different lunar relay architectures and assessing their coverage performance. The moon, as Earth's satellite, is unique in the following ways:

1. Due to tidal locking, the Moon is rotating at the same rate as its revolution of 27.3 days. Thus, surface elements on the nearside always have direct line-of-sight with Earth, whereas those on the far side are permanently shielded. The landing assets on the far side would have to rely on relay orbiter to communicate with Earth.
2. Due to the proximity of the Moon with Earth, Earth's ground stations can cover the nearside of the lunar surface.

We originally attempted to find lunar relay orbits whose coverage would bias towards the far side of the moon, but the slow rotating rate of the Moon proves to be a formidable challenge. The orbits we found are either unrealizable, too unstable, or too far from the lunar surface to be useful. We then considered relay network constellations that provide global coverage of the Moon (not simultaneous) using a combination of circular orbits and elliptical orbits. We performed a systematic search using the following criteria on the candidate constellations:

1. Orbits should be stable to minimize delta-V required for station keeping.
2. The range between an orbiter and a lunar surface element should be small to minimize space loss in communications.
3. To provide high average contact duration across all latitudes.
4. To support high percentage of contact time across all latitudes.
5. To minimize maximum gap time across all latitudes.

For RF communications, for two spacecraft in flight, we consider one spacecraft to have coverage with respect to the other (or vice versa) when they have line-of-sight with each other. For the case between a spacecraft and a lander on the Earth or lunar surface, we impose an additional constraint that that the elevation angle – the angle between the line-of-sight and surface tangential – has to be larger than some minimum value.

We consider three lunar relay architecture options, all communicating with the three sites of the Deep Space Network (DSN) – Goldstone, Canberra, and Madrid:

1) A constellation of three relay orbiters: two at the Polar frozen elliptical orbits, and one at an equatorial circular orbit.
2) One relay orbiter in a 74-day Lissajous orbit at Earth-Moon Lagrange Point L2.
3) One relay orbiter in a 14-day Lunar distance retrograde orbit.

The rest of the paper is organized as follows: Section II introduces three lunar relay candidates for RF communications, and discusses their coverage performance and different pros and cons. Section III describes a multi-hop lunar relay architecture for the optical links, with additional constraints of SEP and SPE are considered. Section IV gives concluding remarks.

II. Lunar Relay Architecture Options for RF Links

We consider three lunar relay architectures and discuss the coverage performance and other pros and cons.

A. Three relay orbiters – two at Polar frozen elliptical orbits, and one at an equatorial circular orbit

All three orbits have a period of 12 hours. The two in the frozen elliptical orbits have their lines of apsides liberating over the North Pole and South Pole respectively [3][4]. The Keplerian elements of the three orbits are summarized in Table 2. The orientations and trajectories of the lunar relay constellation are illustrated in Figure 1.

Table 2 Summary of Keplerian Elements of the Lunar Orbits

Lunar Satellite Orbits	semi-major axis (km)	Eccentricity	Inclination (deg)	Ascending node (deg)	Argument of Perilune (deg)	Mean Anomaly (deg)
12-Hr Circular Equatorial	6142.4	0	0	0	315	0
12-Hr Elliptical North	6142.4	0.59999	57.7	270	270	0
12-Hr Elliptical South	6142.4	0.59999	57.7	0	90	0

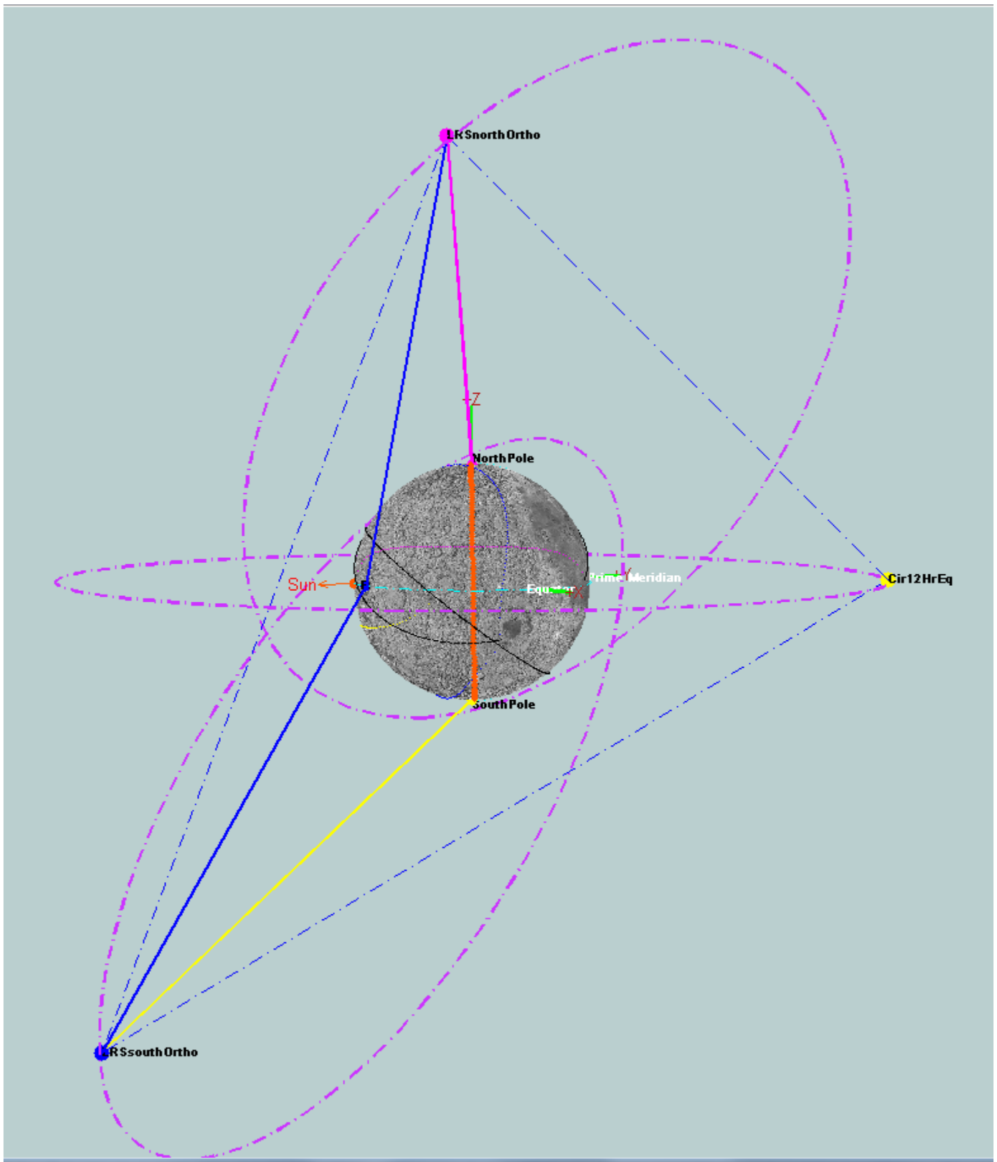

Fig. 1 Notional Lunar Relay Constellation

We performed detailed delta-V analysis for orbit station keeping by propagating the trajectories and taking into account the deterministic gravitational effects of Earth, Moon, and Sun, and the non-deterministic effect of solar pressure.

The coverage performance in terms of average number of contacts per day, average contact duration (hours), total contact time per day (hours), and maximum communication gap (hours) are shown in Figure 2.

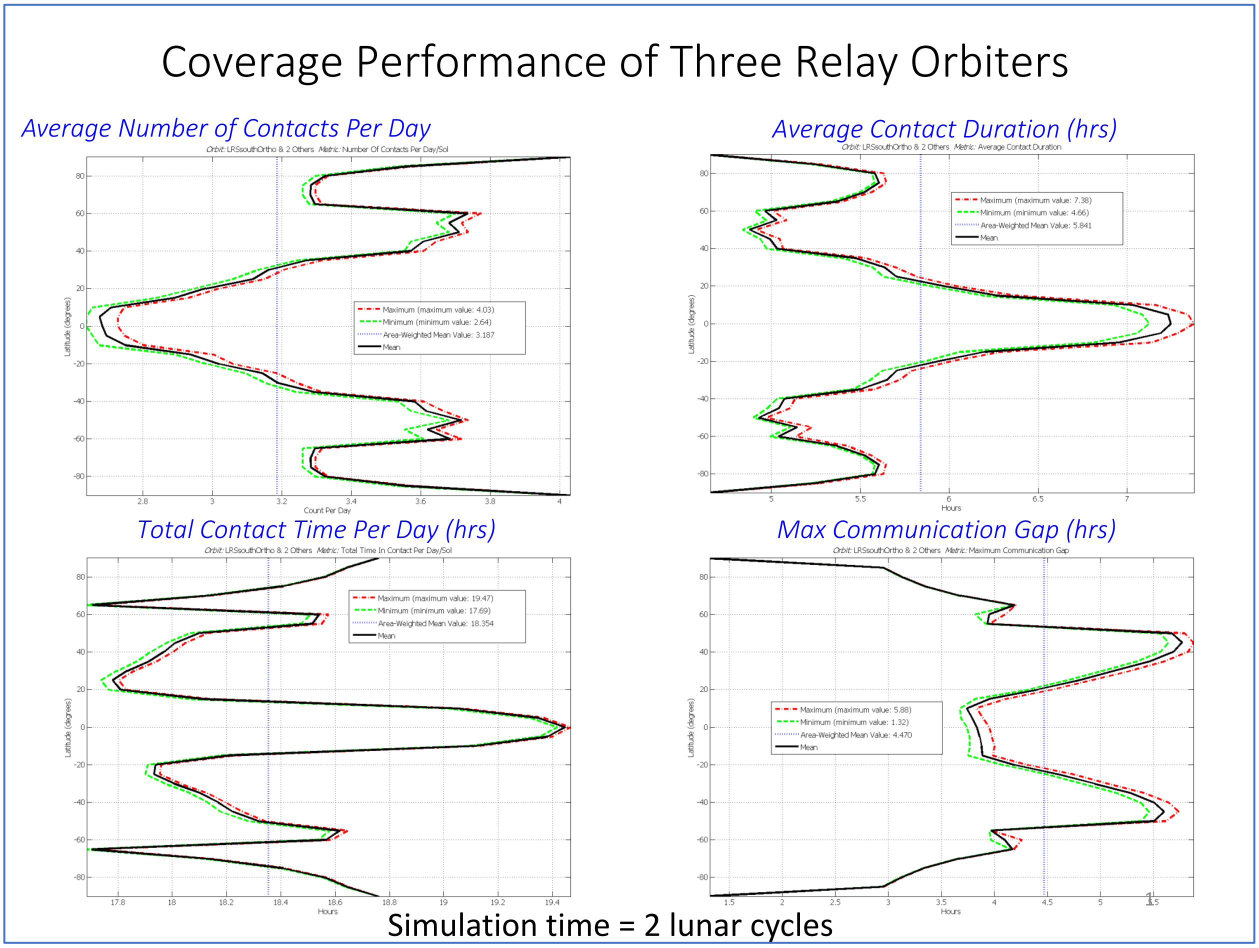

Fig. 2 Coverage Performance of Lunar Relay Option A

The pros and cons of this notional constellation can be summarized as follows:

Pros:

1. This constellation can be built up incrementally based on the lunar mission set – South Pole, Equator, then North Pole.
2. The network offers good and relatively even coverage at different latitudes of the Moon with only three orbiters.
    a. Long contact durations (5 – 7 hours).
    b. Large total contact time per day (17.6 – 19.4 hours).
    c. Short gap time (1.4 – 5.8 hours)
3. The orbiters require low delta-V for station keeping.

Cons:

1. This constellation requires launching three satellites into orbit.

B. One relay orbiter in a 74-day Lissajous orbit at Earth-Moon Lagrange Point L2

This architecture consists of one orbiter in a 74-day Lissajous orbit at the Earth-Moon Lagrange Point L2. This orbit has good visibility of the lunar far-side, and is designed to favor the lunar South Pole. It is assumed that the near-side of the Moon be covered by Earth's stations directly. The orientations and trajectories of the lunar relay orbiter are illustrated in Figure 3. This orbit is relatively unstable and requires constant station-keeping, preferably using solar electric propulsion.

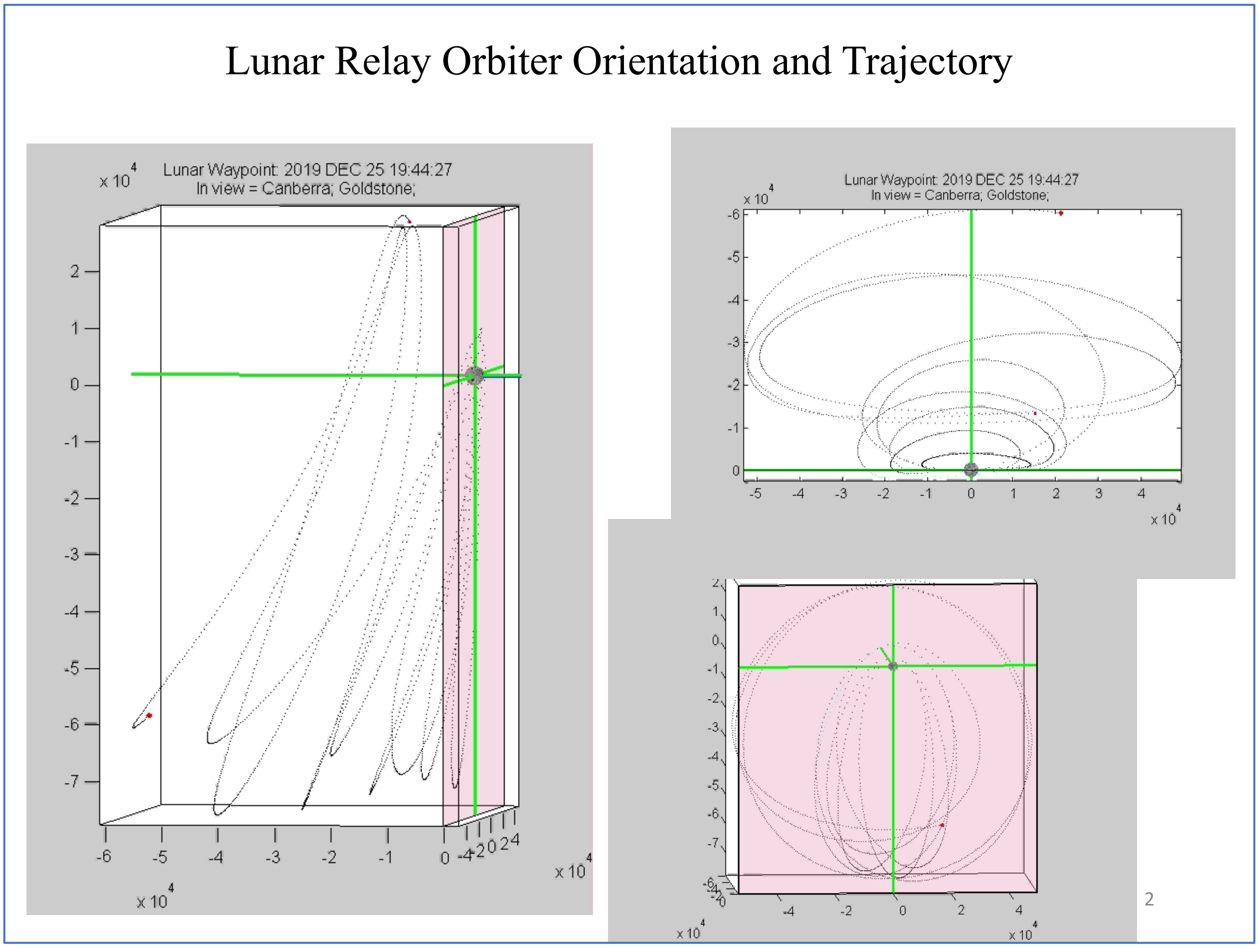

Fig. 3 Notional Lunar Relay Orbiter in a 74-Lissajous Orbit at Earth-Moon L2

The coverage performance in terms of average number of contacts per day, average contact duration (hours), total contact time per day (hours), and maximum communication gap (hours) are shown in Figure 4. Note that the above coverage statistics is shown as global maps as a function of latitude and longitude. As the near-side of the Moon is expected to be covered directly by Earth's stations, the region bounded by longitudes -90° and +90° is of low significance. Also, the lack of DSN coverage in some regions in the South Atlantic Ocean and the Indian Ocean contributes additional gaps in the end-to-end data delivery. It is found that an additional ground site in Hartebeesthoek, South Africa, can help to eliminate many of the gaps.

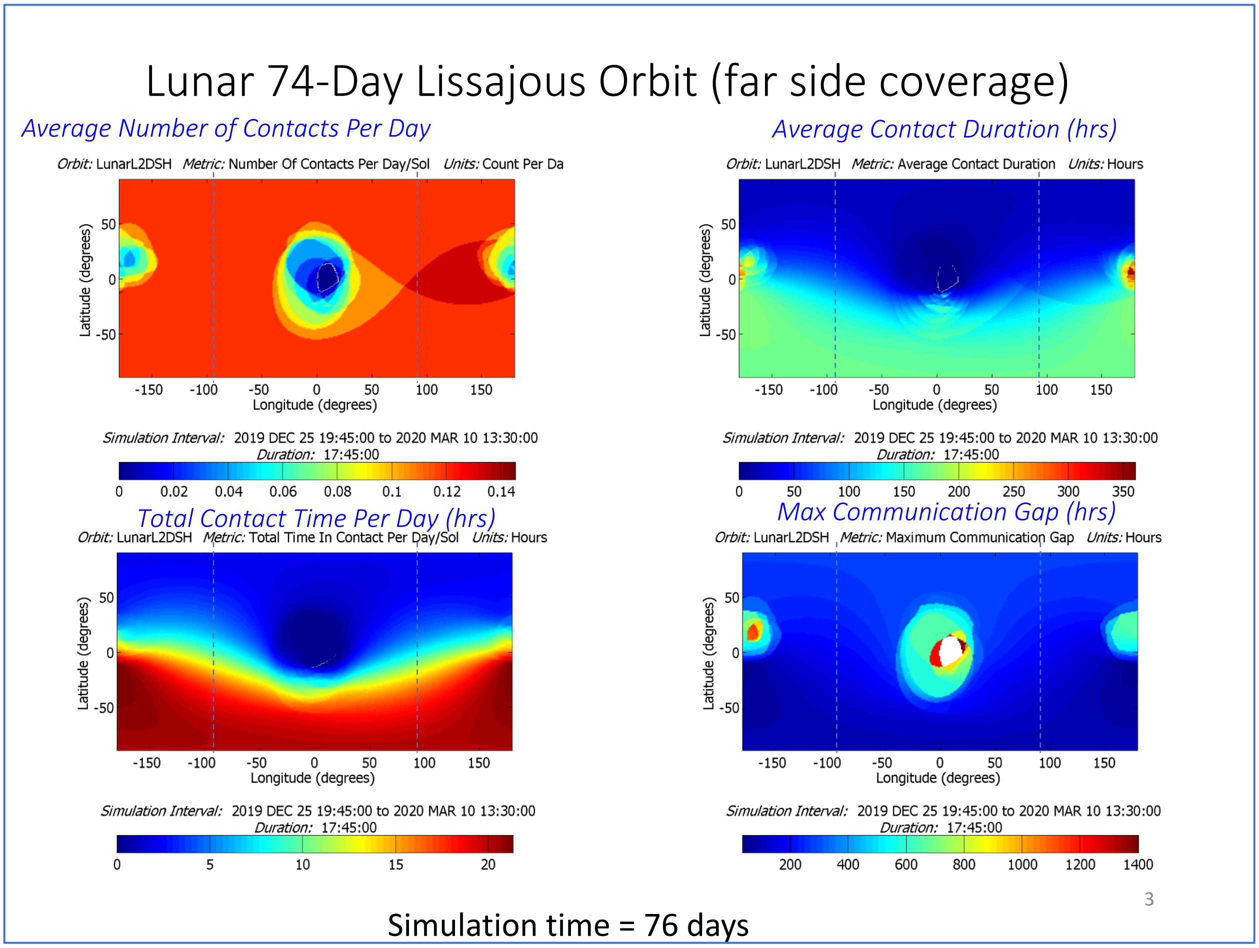

Fig. 4 Coverage Performance of Lunar Relay Option B

Highlights of coverage performance of the 74-day Lissajous orbit is given below:

1. This relay architecture covers most of the lunar far side, except the far side equator.
2. This orbit favors the far side South Pole.
3. There are 0.8 – 1.2 contacts per 10 days.
4. Average contact is between 20 to 170 hours.
5. Range can be as long as 90000 km.
6. Communication gaps can be 90 hours or more.
7. South Pole's has no or low visibility with Earth, and has to rely on the relay orbiter.
8. An additional ground station in Southern Hemisphere (e.g. Heetebeesthoek, South Africa) helps to eliminate the daily short gaps, but does not increase the time in view significantly.

C. One relay orbiter in a 14-day lunar distance retrograde orbit

This architecture includes one relay orbiter in a 14-day lunar distance retrograde orbit. The orientations and trajectories of the lunar relay orbiter are illustrated in Figure 5.

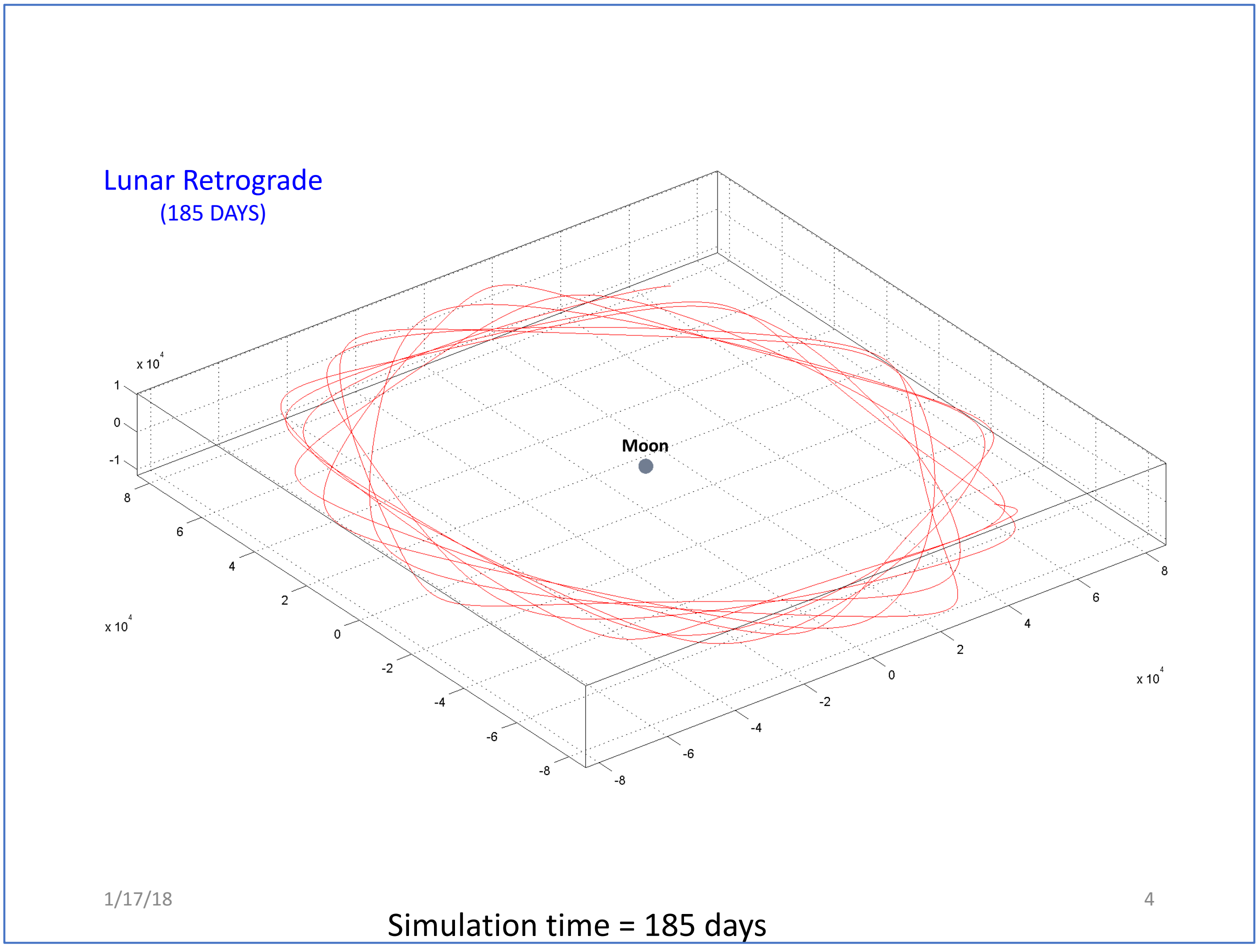

Fig. 5 Notional Lunar Relay Orbiter in a Distance Retrograde Orbit

The coverage performance in terms of an average number of contacts per day, average contact duration (hours), total contact time per day (hours), and the maximum communication gap (hours) are shown in Figure 6.

Summary of coverage performance of the lunar retrograde orbit is as follows:

1. This orbit provides coverage globally, except the poles.
2. The coverage favors the equator.
3. This orbit provides one contact approximately every 7 days between +/- 70° latitude.
4. Average contact time is between 80 and 130 hours between +/- 70° latitude.
5. Range could be as long as ~90,000 km.
6. Communication gaps could be 250 hours or more between +/- 70° latitude.
7. The orbit is very stable.

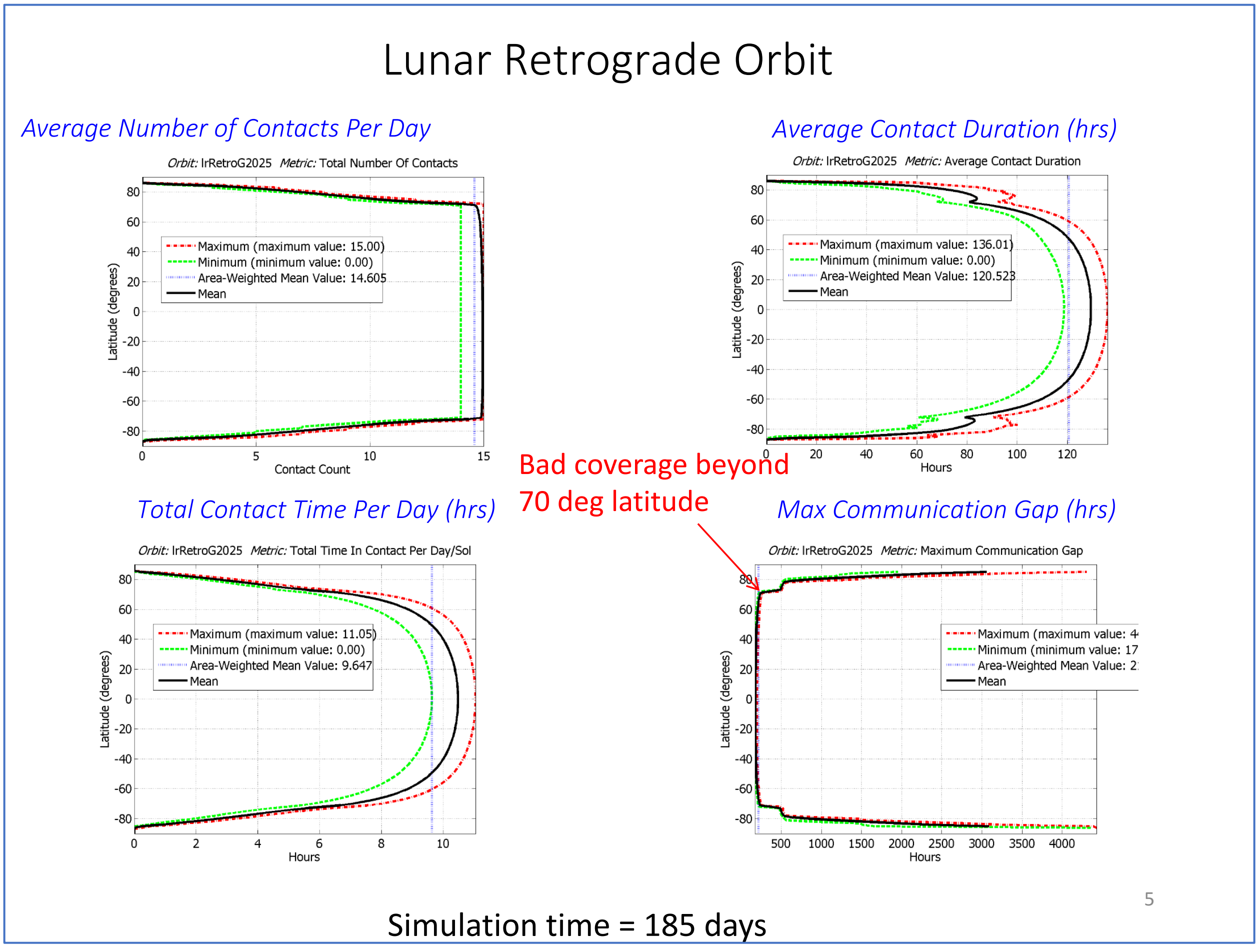

Fig. 6 Coverage Performance of Lunar Relay Option B

III.Notional Lunar Relay Architecture for Optical Links

For the optical links, we consider a lunar relay architecture that consists of:

1. A lunar relay orbiter in a 74-day Lissajous orbit at the Earth-Moon Lagrange Point L2 to support lunar assets at the back-side and the polar regions of the Moon. This is the same orbit as Option B for the RF link.
2. Three Earth-orbiting relay orbiters at three Tracking and Data Relay Satellite System (TDRSS) locations: TDRS-7(G), TDRS-11(K), and TDFRS-8(H).
3. Three optical ground telescopes that support the TDRSS satellites at White Sands (for TDRS-7), Guam (for TDRS-11), and Tenerife, Spain (for tdrs-8).

This optical relay architecture and data flow is illustrated in Figure 7. For optical communications, in addition to the aforementioned RF constraints in considering coverage, we investigate the time profiles of Sun-“Earth”-Probe (SEP) angle for return links, and Sun-Probe-“Earth” (SPE) angle for forward links. SPE and SPE angles determine the amount of sunlight (noise) that goes into the detector of the telescope, thus affect the capacity of an optical link. It is generally assumed that there is no coverage when SEP < 10°, or when SPE < 3°. For a surface-to-space link, we assume no coverage when the elevation angle is less than 10°.

Unlike in the RF cases that we evaluate coverage performance in terms of the statistics on average number of contacts per day, average contact duration (hours), total contact time per day (hours), and maximum communication gap (hours), we express the coverage (or the outage) as timelines of optical link availability based on some dominant factors like SEP angle, elevation angle, etc.

One can argue that certain links in this relay architecture can be better served with RF, for example, the TDRSS to ground links. However, to illustrate the effects of SEP and SPE to the coverage performance, we assume all links are optical. We also assume that the TDRSS satellites would cover lunar assets on the near-side of the Moon via a 2-

hop link (2 and 3). Lunar assets on the Moon's far side and at the Poles would communicate via a 3-hop link (1, 2, and 3). For coverage analysis, we consider two points on the lunar surface: one at lunar S. Pole, and one at lunar near-side at the equator (long/lat = 0˚, 0˚).

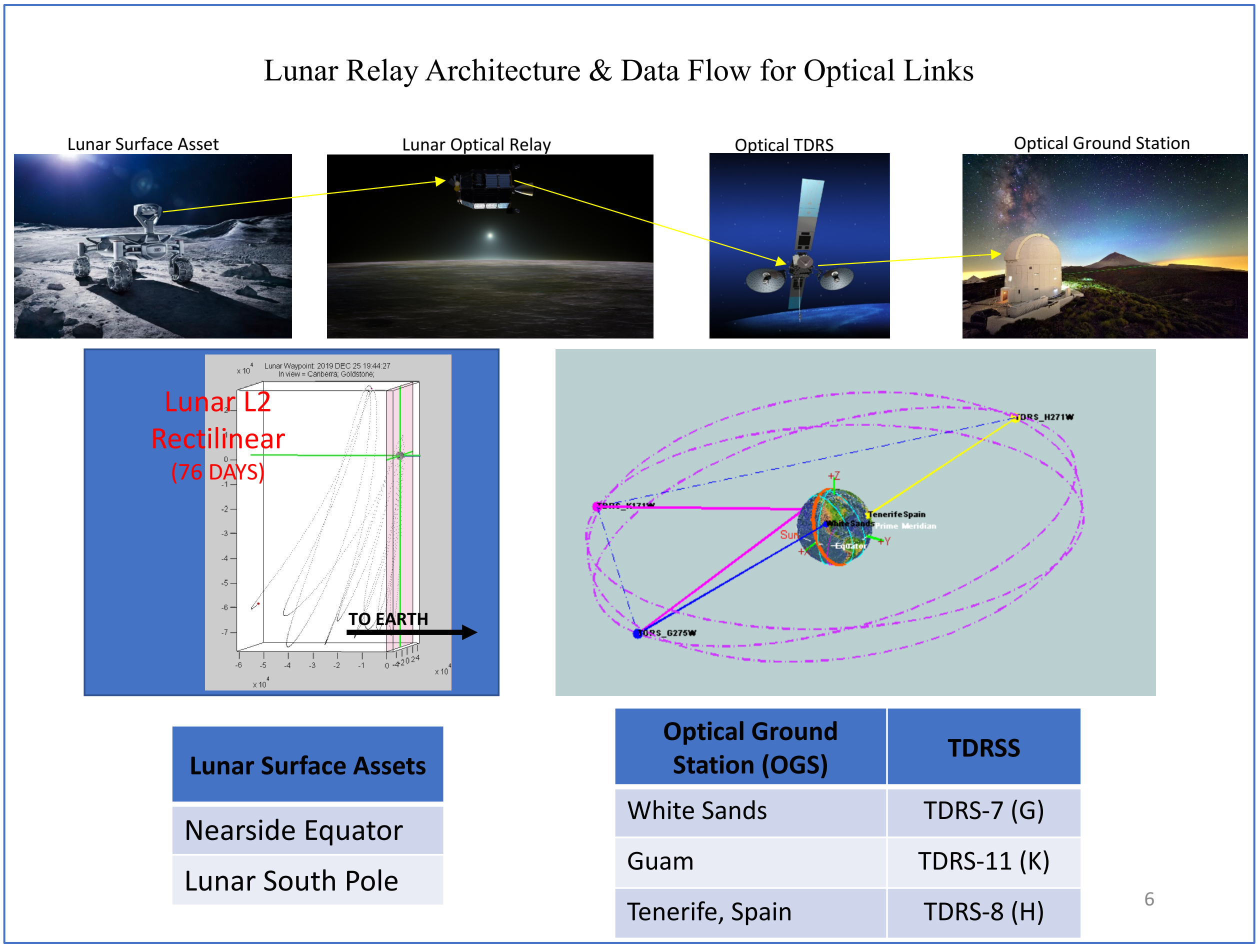

Fig. 7 Notional Lunar Relay Architecture and Data Flow for Optical Links

Based on the lunar relay architecture and data flow depicted in Figure 7, we consider the coverage of the following four optical links:

A. Lunar South Pole to L2-Relay
B. L2-Relay to TDRSS
C. Lunar near-side (longitude/latitude = 0˚/0˚) to TDRSS
D. TDRSS to optical ground telescopes

A. Lunar South Pole to L2-Relay Link

This is a surface-to-space link, and the coverage is dominated by the elevation angle. The coverage performance repeats every 74 days, which is the period of the Lissajous orbit. The elevation angle as a function of time is shown in Figure 8. There are 9 gaps within this period ranging from 3.8 hours to 89.3 hours.

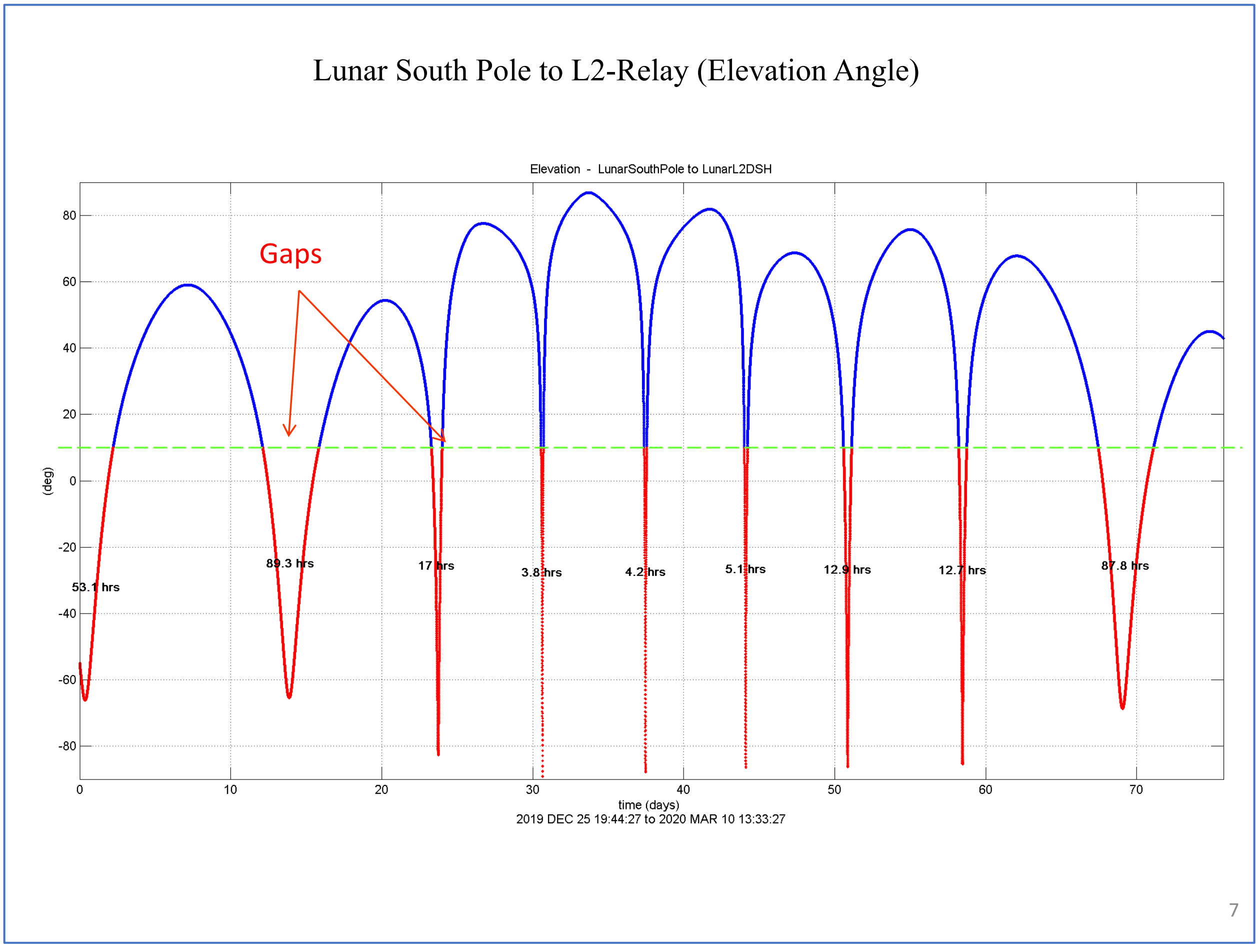

Fig. 8 Coverage Performance of the Lunar South Pole to L2-Relay Link

B. L2-Relay to TDRSS Link

This is a space-to-space link, and the coverage is dominated by the SEP angle. Note that the Moon revolves around Earth every 27.3 days, and the Earth-Moon line (thus the Earth-Probe line) spans approximately 360° (one revolution) with respect to the Earth-Sun line during this time. Roughly speaking the outage, which we define as SEP < 10°, is approximately 1.5 days every 27.3 days. That is what we observe in Figure 9 that shows the SEP angle as a function of time.

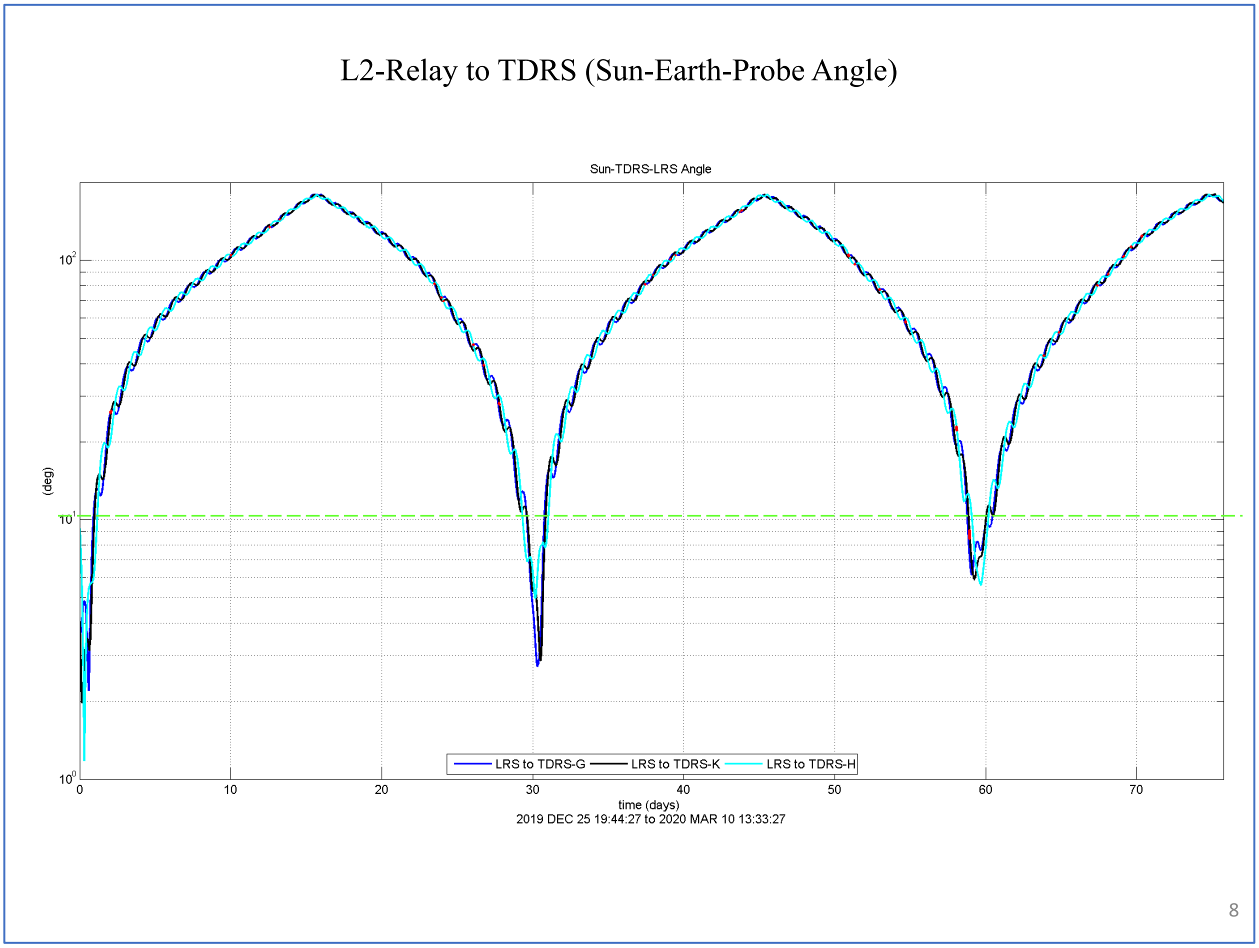

Fig. 9 Coverage Performance of the L2-Relay to TDRSS Links

C. Lunar near-side (longitude/latitude = 0º/0º) to TDRSS Link

Due to tidal-locking of the Moon, the Moon's near-side at is always facing Earth. As in the above Case B, that the Earth-Probe line spans approximately 360˚ with respect to the Earth-Sun line during one revolution of the Moon around Earth (27.3 days). As shown in Figure 10, the outage is approximately 1.5 days every 27.3 days, similar to Case B.

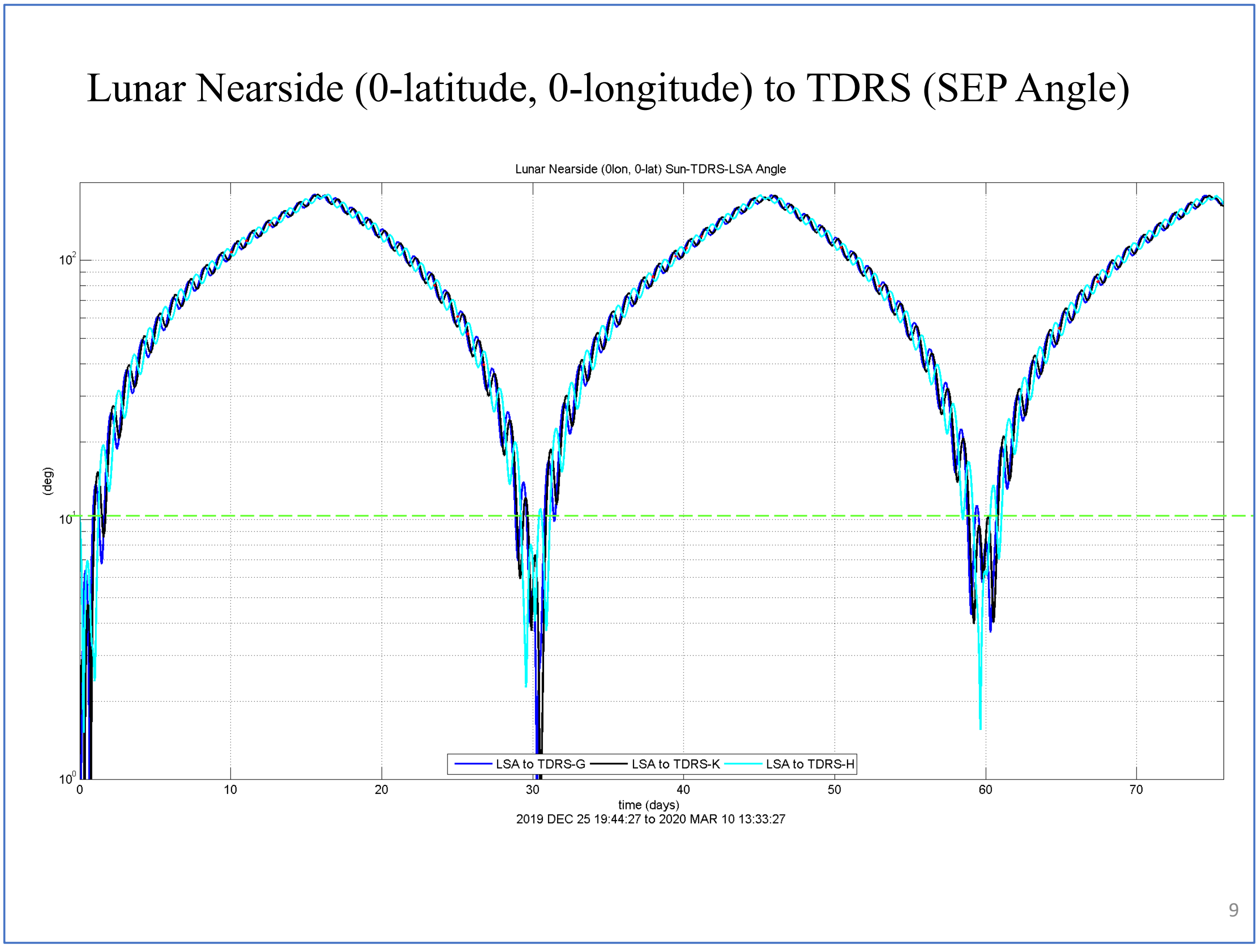

Fig. 10 Coverage Performance of the Lunar Near-Side to TDRSS Links

D. TDRSS to Optical Ground Telescopes Link

The TDRS satellites are in Geostationary orbits, which revolve around Earth once every 24 hours. Thus, we expect a fast-varying periodic dip of SEP angle every day. However, Earth's rotation axis is tilted 23.5° with respect to the Ecliptic plane, and this creates a slow-varying SEP profile with a period of a year. The resulting SEP profile is shown in Figure 11. Note that there are periods of time (20+ days) when the SEP angle does not go below 10°.

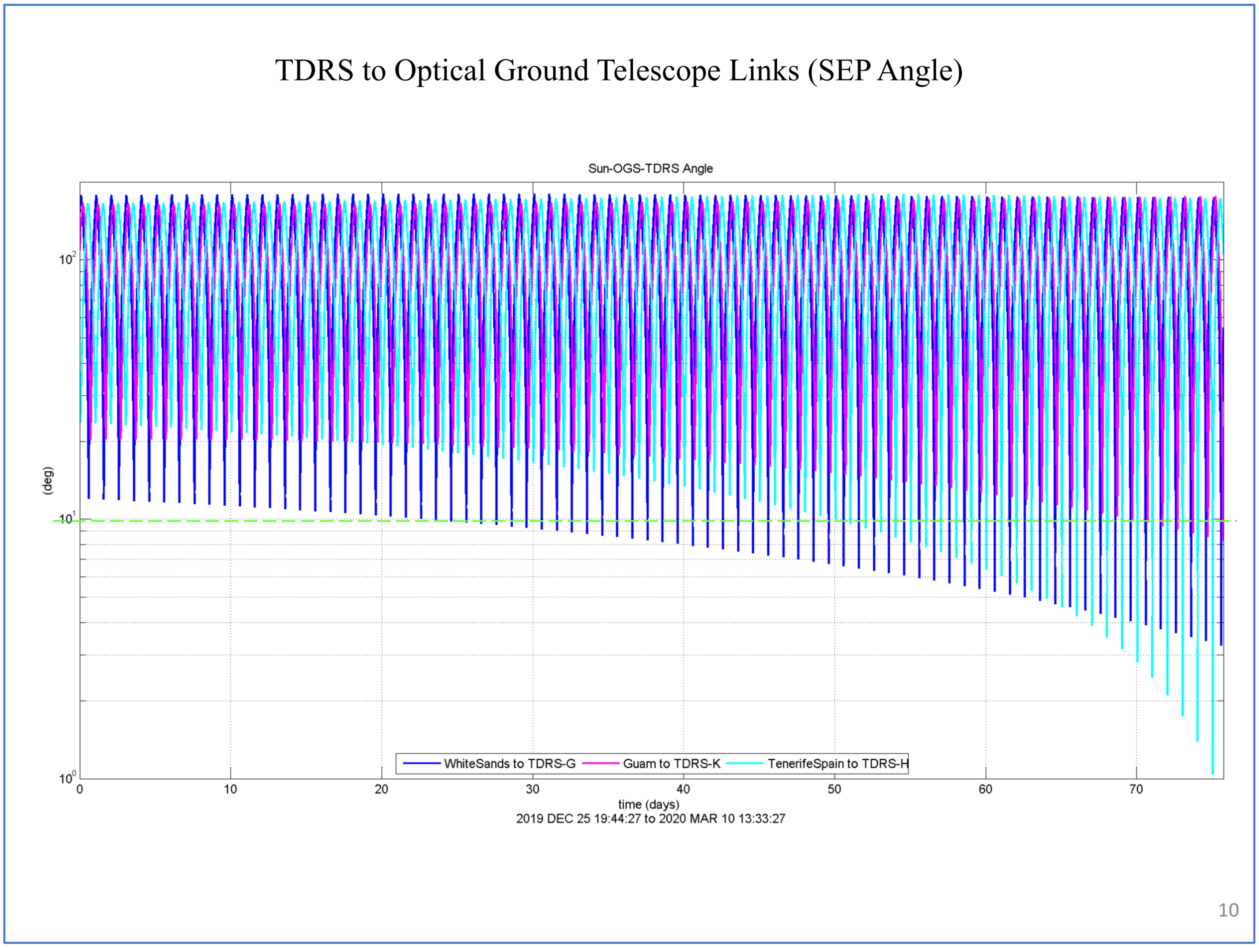

Fig. 11 Coverage Performance of the TDRSS to Ground Telescope Links

IV.Conclusion

This paper describes our effort of searching different lunar relay architectures and assessing their coverage performance and others pros and cons for RF and optical links.

An interesting finding is that unlike elevation angle that varies with the period of a "day" of an observation frame (e.g. Earth, Moon, or Mars), the SEP and SPE angles vary according to the synodic period between two observation frames, which can be long. For the Earth-Moon system, it is 27.3 days. Beyond Moon, for the Earth-Mars system, it is 1.9 years. For the Earth-Jupiter system, it is 11.9 years. The long synodic period translates into long duration of high and low performances of an optical link, which can be an operational challenge using optical communications for those missions.

Acknowledgement:

The authors would like to thank Wallace Tai of the Jet Propulsion Laboratory for providing information on Table 1. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). The research was supported by the NASA's Space Communications and Navigation (SCaN) Program.

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