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Interagency Operations Advisory Group
Lunar Communications Architecture Working Group

The Future Lunar Communications Architecture

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Document Change Log

Revision	Issue Date	Affected Sections or Pages	Change Summary
-	25 September 2019		Initial issue of the final report V1.0
V1.1	10 October 2019	Table 1, Page 9	Updates on the launch years and space vehicle information of the CNSA Chang'e missions.
		Table 3, Page 13	Updates on the frequency bands used by the Chang'e missions.
V1.2	1 February 2020	Table 4 Page 20	Added a statement about CCSDS VCM (DVB-S2, SCCC, or LDPC-VCM) to the Moon-to-Earth RF high rate link.
V1.3	31 January 2022	Member list	Replaced 'ESA ESOC' with just 'ESA' Updated the member list
		Change Log	Corrected date (year) in change log for V1.2
		Introduction	Removed reference to CLPS
		Section 2, page 7	Updated the timeframe and ore references to the Shield Zone of the Moon

			Changed ‘EM-1’ to ‘Artemis-1’ Changed ‘EM-2’ to ‘Artemis-2’
		Table 1, page 10	Updated missions from CNES, ESA, ISRO and NASA
		Table 3, page 16	Updated missions from CNES, ESA, ISRO and NASA
		Table 4, page 28	Updated references to the shielded zone on the Moon for UHF operation and the ‘Lunar Surface to Lunar Surface’ section
		Figure 1, page 35	Updated Figure and added additional figures with surface assets
		Section 4.2, page 38	Updated reference to the shielded part of the Moon
		Section 4.4, page 41	Update to the surface networks section
		Table 5, page 47	Added CCSDS 883.0-B-1 to this table
		Section 4.7, page 49	Added a discussion section of the impact of commercial operators in lunar communications
		Table 8, page 56	Updated table with information on Chandrayaan-3
		Appendix B: References, page 70	Updated SFCG lunar reference to RC3
		Appendix B: References, page 70	Added in the references to 3GPP and 5G

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1. Introduction

The Lunar Communications Architecture Working Group (LCAWG) has been tasked by the IOAG to conduct a study for defining a future Lunar Communications Architecture that will facilitate potential cross support to Lunar missions by communication assets owned and/or operated by the IOAG member agencies and their affiliated companies in the private sectors. Such an architecture is intended to serve as the framework for the IOAG member agencies, individually or collaboratively, to establish their Lunar network(s) so that communication assets in the network(s) will be interoperable with each other at the network, data link, and physical layers.

The scope of the study can be summarized as follows:

- Define the communications architecture based on some architecture requirements and essential concepts of operation.
- The architecture defined must take into account these elements: Lunar science orbiters, Lunar exploration orbiters, Lunar surface mobile and stationary vehicles, Lunar relay orbiters, Earth orbiting relays that provide service to lunar systems, Lunar Ascent & Descent modules, and associated Earth ground stations and mission operations centers.
- Communications links covered by the architecture should include: Earth-Moon link, Lunar proximity link, Lunar cross link, Lunar surface vicinity link, Earth orbiting relay link, and Earth space link extension.
- Address the Space internetworking aspect of the architecture.
- Define the specific services provided by the network communication assets within the Architecture to user missions.
- The physical layer of the architecture should consider both RF and optical communications including specific frequency/wavelength bands.
- The study will address user missions in two categories, robotic and human exploration, covering the timespan from 2018 to 2030.

In view of the formulation phase activities being conducted for the international Lunar Orbiting Platform-Gateway (LOP-G) initiative individual members of the LCAWG pro-actively worked with the Gateway program to establish a unified position on key technical subjects and to ensure a coherent Lunar communications architecture between the two activities. To that end, in January 2018, in response to an IOAG action item, IOAG AI-21-16, a white paper containing a set of recommendations on the down-selected frequency, modulation, ranging, and coding for the future lunar architecture was provided as an input to the LOP-G requirement document.

Note: The LOP-G is now called the Lunar Gateway or simply the Gateway and is only referred to as 'Lunar Gateway' for the remaining sections of this report.

This report documents the key results of the architecture study. Naturally, it also includes the response to IOAG AI-21-16.

The working group recognizes that there will be a varied amount of missions that will be operating in cis-lunar space. This includes commercial and institutional, but also systems that are currently being developed that will be in lunar orbit before 2020. This paper reflects this, with the recommendation being spilt into legacy and future missions. Both categories follow the current SFCG recommendations.

2. Lunar Mission Set During 2018 – 2030 Timeframe

Table 1 summarizes all the known missions launched and planned to be launched during the 2018 -2030 timeframe. It is the subset of a more complete data sheet that shows all the communication capabilities, e.g., frequency bands, modulation and coding schemes, and IOAG services at data link, network, and file layers, provided by each mission.

An analysis on this mission set has led to a few important observations that have ramifications to the Lunar communications architecture:

- Unprecedented number of missions: There are more than 40 missions, approximately 80 space vehicles planned by or involving 10 space agencies during this era. Endeavors by private sectors, e.g., Moon Express, Astrobotic, Intuitive Machines, SpaceX and Blue Origin, are not listed here due to commercial sensitivity (non-disclosure agreements), and lack of involvement of IOAG agencies.

- Inter-agency cross support: Approximate 19 missions would require cross support by communication assets of other agencies; 8 missions yet to decide.

- The trend toward Lunar surface exploration: At least 16 missions have been planned to deploy a lander, a rover, or both.

- The emergence of Lunar relay orbiters: There will be at least 4 Lunar relay orbiters deployed to serve landed vehicles.

- The abundance of SmallSat/CubeSat missions: There will be 10 CubeSat lunar missions (as the secondary launched payload to Artemis-1) and 2 SmallSat missions. There will also be a set of CubeSat lunar missions associated with the Artemis -2 launch. The actual number is not known at this time.

- The mission mix of human crewed and robotic missions: A significant change from the current lunar exploration is the presence of crewed vehicles, in orbit and on lunar surface, championed by the international Lunar Gateway program.

- The trend toward commercially “owned” missions: A number of companies have set their sights on the Moon, and they’re ramping up their plans to deliver spacecraft to its orbit and surface.

- The advancement of new technology through Lunar exploration: Predictably, the wave of lunar missions will spur many "tipping point technologies" to be infused for supporting the scientific investigations and human exploration.
- The potential of Lunar far side science: Because the far side of the Moon is shielded from radio transmissions from the Earth, it is a good location for placing radio telescopes for use by astronomers. The mission set for this period also features quite a few landers and rovers on the far side of the South Pole. A sample-return mission to the South Pole-Aiken Basin, for example, would provide precious materials for scientific information concerning the interior of the Moon. The ITU-R RA.479-5 reference [41] on the Shielded Zone of the Moon states: "frequencies between 300 MHz and 2 GHz should be reserved to Radio Astronomy”. Article 22-Section V of ITU Radio Regulation[39], dedicated to protection of Radio Astronomy in the SZM, required coordination with Radio Astronomy, even when filing request is made on a non-interference basis in the frame of ITU Radio Regulation article 4.4.

Given the above, certain architecture requirements must be considered by our study for Lunar space communications:

- The wide <u>diversity</u> of the types of Lunar missions to be accommodated by the space communications architecture during this decade: This inevitably leads to an architecture that is not quite homogenous throughout.
- The high degree of <u>interoperability</u> among the missions for the international Lunar campaign: The spacecraft and other types of flight assets provided by the partnering agencies and commercial sectors must be implemented according to a set of common interface standards at, at a minimum, physical and space data link layers, and preferably at network layer as well.
- The <u>cross-supportability</u> of the communications service providing systems to certain collaborative missions: The ground stations of Earth Network owned by the IOAG space agencies will continue to provide cross support services to each other’s Lunar missions. Newly introduced during this era are the Lunar relay orbiters, dedicated relay or provisional, that will provide new types of services, i.e., the Lunar relay services, and the commercial ground stations capable of deep space

communications. It is crucial for them meet the architecture requirements[26] for cross support defined by the CCSDS.

- The dynamicity in capabilities, in terms of G/T and EIRP, demanded on some of the service providing systems: Driven by some high-rate science missions (synthetic aperture radar and multi-spectrum/hyper-spectrum imagers) and human exploration (high-resolution videos), the Lunar communications will venture into an unprecedent high-rate regime. Yet, there will be many low-rate missions, e.g., small commercial landers. To some service providing systems this may mean their ability to provide a broader dynamic range of link capabilities.
- The scalability and expandability of the overall architecture to accommodate future technology infusion: As always, the infusion of any new communications technology will have some ramifications to the end-to-end architecture. Chief examples of new technologies in the near term are optical communications and real-time positioning for the Lunar surface elements.
- The security protection of the end-to-end Lunar communications paths: The security architecture must be addresses as an integrated and inherent part of the Lunar communications architecture.
- The backward compatibility with the existing communications infrastructure(s) resulting from decades of investment by space agencies: To the degree possible, the architecture must use, the existing communications architecture, which is more Earth Network-centric and dominated by point-to-point Space-Earth links, as the basis and be extended into an interplanetary network architecture or space internetworking architecture. As the systems migrate towards new era, infusing new capabilities and preserving existing capabilities/assets must be traded on an individual-by-individual basis. However, frequency changes must be done in the frame of a transitional period when the Radio Regulations and ITU REC 479-5 [42] regarding the protection of Radio Astronomy in the SZM is not respected. Operational measures, such as the progressively switching off non-ITU compatible transmissions in the SZM maybe a mitigation in this transitional period.

Table 1 Lunar Missions During Timeframe of 2018-2030

Lunar Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets♪
Chandrayaan-2	2019	ISRO	3	Orbiter, S. Pole far-side lander/rover	NASA	IDSN, DSN
Chandrayaan-3	2022	ISRO	2	S. Pole far-side lander/rover	NASA	IDSN, DSN
Chang'e 4	2018	CNSA	3	Orbiter, S. Pole far-side lander/rover	ESA	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina), ESA DSN
Chang'e 5	2020	CNSA	4	Orbiter/lander/ascender/sample return capsule	ESA	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina)
Chang'e 6	2023	CNSA	4	Orbiter/lander/ascender/sample return capsule	ESA	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina)
Chang'e 7*	2027	CNSA	3	Orbiter/lander/rover S. Pole research station	[TBD]	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina)
Chang'e 8*	2028	CNSA	2	Lander/rover/flying detector for S. Pole in-situ resource utilization	[TBD]	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina)
Beresheet Lander	2019	SpaceIL	1	Small lander	NASA, DLR	DSN, DLR stations
Beresheet-2 Lander	[TBD]	SpaceIL	3	Orbiter and 2 landers	[TBD]	[TBD]
Korea Pathfinder Lunar Orbiter (KPLO)	2022	KARI	1	Orbiter	NASA	KDSA, NEN, DSN
Korean Lunar Mission Phase 2	2020s	KARI	3	Orbiter/lander/rover	[TBD]	KDSA and other assets
Luna-25 Lander	2022	Roscosmos	1	Lander on S. Pole	ESA	RFSA Network
Luna-26 Orbiter	2024	Roscosmos	1	Orbiter	ESA	RFSA Network
Luna-27 lander*	2026	Roscosmos	1	Lander on S. Pole	ESA	RFSA Network
Luna-28*	2027	Roscosmos	2	Lander on S. Pole & sample return	ESA	RFSA Network
Luna-29*	2028	Roscosmos	1	Rover on S. Pole	[TBD]	RFSA Network
Smart Lander for Investigating Moon (SLIM)	2021	JAXA	1	Lander	None	JAXA Network, DSN

Lunar Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets♪
JAXA polar exploration	2023	JAXA	1	Lander/Rover	ISRO	JAXA Network, DSN
Commercial Lunar Payload Services (CLPS)	2021-2028	NASA/ Industry	10	Small landers with NASA payloads	[TBD]	DSN/NEN, Lunar Gateway
Cislunar Autonomous Positioning System Technology Operations & Navigation (CAPSTONE)	2021	NASA	1	CubeSat orbiter for technology demo	None	DSN, MSU
Lunar Node-1	2022	NASA	1	Lunar orbiter	None	DSN
PRIME-1	2022	NASA	1	Lunar orbiter	None	DSN
Lunar TrailBlazer	2023	NASA	1	SmallSat orbiter	None	DSN, MSU
Volatile Investigating Polar Exploration Rover (VIPER)	2023	NASA	1	Rover	None	DSN
Lunar Surface Science missions	2023	NASA	1	Mid-sized robotic rover for science & exploration	[TBD]	DSN/NEN, Lunar Gateway
Lunar Communications Pathfinder*	2024	Goonhilly, SSTL, UKSA, ESA	1	Relay Orbiter	ESA	Goonhilly stations, ESA DSN
Lunar Gateway – Power Propulsion Element (PPE) + Habitation & Logistics Outpost (HALO)	2023	NASA	1	Orbiter in Near-Rectilinear Halo Orbit (NRHO)	ESA, JAXA, CSA	DSN, NEN, ESA DSN
Lunar Polar Exploration (LUPEX)	2025	JAXA/ISRO	1	Lunar rover and lander in S. Pole	NASA	IDSN, JAXA network, DSN
Lunar Relay Network	2024	NASA	2-3	Relay orbiters in 12-hour frozen orbit	Commercial	DSN, NEN, ESA DSN
Lunar Gateway – International Habitation Module (I-Hab)	2025	ESA, JAXA	1	NRHO	ESA, JAXA, CSA	DSN, NSN, ESA DSN
ISRU Demo	2026	NASA	1	Lunar surface	[TBD]	DSN, NSN

Lunar Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets♪
Lunar Gateway – European System Providing Refueling. Infrastructure & Telecommunications (ESPRIT)	2027	ESA	1	NRHO	ESA, JAXA, CSA	DSN, NSN, ESA DSN
Exploration Command Module (ECM)	2027	NASA	1	NRHO	ESA, JAXA, CSA	DSN, NSN, ESA DSN
Lunar Terrain Vehicle	2025	NASA	1	EVA vehicle	NASA	DSN, NSN, ESA DSN
Taiwan Lunar Science Orbiter*	2025	NSPO	1	SmallSat Orbiter	[TBD]	DSN [TBD]
Gateway Logistics Services (GLS-1 thru GLS-7)	2025 - 2031	NASA	7	Transit to NRHO orbit	ESA, JAXA, CSA	DSN, NSN
Habitable Mobility Platform (HMP)	2028	NASA/JAXA	1	Cargo lander	ESA, JAXA, CSA	DSN, NSN
Foundational Surface Habitat (FSH)	2029	NASA	1	Cargo lander	ESA, JAXA, CSA	DSN, NSN, ESA DSN, JAXA network
Geophysical Network	2030	NASA	2	Orbiter and Lander	[TBD]	DSN, NSN
Fission Surface Power	2029	NASA	1	Lunar S. Pole	[TBD]	DSN, NSN
ISRU Pilot Plant	2029	ESA	1	Lunar S. Pole	[TBD]	ESA DSN
EL3 (European Large Logistic Lander) Mission 1	2029+	ESA	1-2	Lander with cargo and/or scientific payload (including potentially mobile element)	[TBD]	ESA DSN, Lunar Gateway (TBC)
CLTV (Cis Lunar Transfer Vehicle) Mission 1	2027+	ESA	1	Multi-purpose (cargo , refuelling) transfer vehicle to lunar orbit	ESA	ESA DSN
VMMO (Volatile and Mineralogy Orbiter)	202x	ESA	1	Cubesat	[TBD]	Lunar Pathfinder[TBC] or ESA DSN
LUMIO (Lunar Meteroid Impacts observer)	202x	ESA	1	Cubesat	[TBD]	Lunar Pathfinder[TBC] or ESA DSN

Lunar Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets♪
Moonlight / LCNS	2026-2027	ESA	3+ (TBC)	Lunar Communications and Navigation Service	[TBD]	[TBD]
Pressurized Crew Rover	2029	JAXA	1	Lunar S. Pole	[TBD]	[TBD]
Transit Habitat	2030	NASA	1	Lunar surface	ESA, JAXA, CSA	DSN, NSN, ESA DSN, JAXA network
Artemis-1/Orion	2022	NASA	1	Orbiter	SANSA, JAXA	DSN, NEN, Hartebeesthoek (HBK), JAXA Network [TBD]
Artemis-2/Orion	2023	NASA	1	Orbiter	SANSA, JAXA [TBD]	DSN, NSN, Hartebeesthoek (HBK), JAXA Network [TBD]
Artemis-3/Orion	2024	NASA	1	Orbiter	[TBD]	DSN/NSN, Lunar Gateway
Artemis-3/Human Landing System (HLS)	2025	NASA	3	HLS: descent, ascent, & transfer modules	[TBD]	DSN/NSN, Lunar Gateway
Artemis-4*, -5*, -6*, -7*, -8*	2025- 2030	NASA	20	Orion and HLS (descent, ascent, transfer modules)	[TBD]	DSN/NSN, Lunar Gateway
Lunar Flashlight	2023	NASA	1	Artemis co-manifest CubeSat orbiter [TBD]	JAXA [TBD]	DSN, MSU
SkyMage	2023	US Air Force Research Lab	1	PNT Technology demonstration	None	Commercial ground stations
Lunar IceCube	2022	NASA	1	Artemis-1 co-manifest CubeSat orbiter	JAXA [TBD]	DSN, MSU
LunaH-Map	2022	NASA	1	Artemis-1 co-manifest CubeSat orbiter	JAXA [TBD]	DSN, MSU
ArgoMoon	2022	ASI	1	Artemis-1 co-manifest CubeSat orbiter	NASA	Sardinia DSA, DSN (i.e. Goldstone, Madrid, Canberra)
Omotenashi	2022	JAXA	1	Artemis-1 co-manifest CubeSat lander	NASA	JAXA Network, DSN [TBD]

Lunar Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets♪
Equuleus	2022	JAXA	1	Artemis-1 co-manifest CubeSat orbiter	NASA	JAXA Network, DSN [TBD]
Cislunar Explorer	2022	NASA	1	Artemis-1 co-manifest CubeSat orbiter		DSN, MSU
Lunar InfraRed Imaging (LunIR)	2022	NASA	1	Artemis-1 co-manifest CubeSat orbiter	DoD	AFSCN
Artemis-2 thru -8* CubeSat/SmallSat	2023-2028	NASA	TBD	Artemis co-manifest CubeSat/ SmallSat orbiters/landers	[TBD]	DSN/NSN, MSU

Color codes for cell fills:
Gray: Currently flying or past missions.
Green: Phase-1 missions (2021-2025).
Orange: Phase-2 missions (2025 -2030).
Blue: Cubesat/Smallsat as co-manifested payload for Artemis launch vehicle
Footnotes:
*Proposed mission or mission concept in planning

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3. Frequency, Modulation, Coding, Ranging, and Link Protocol

3.1. Frequency, Modulation, Coding, and Space Data Link Protocols in Current Paradigm

Since a number of missions in Table 1 were planned and designed prior to the IOAG's LCAWG effort, often without the need or benefit of any multi-agency coordination, it is understandable that any proposed Lunar communications architecture for the future may exhibit some significant deviations from the current paradigm. This phenomenon is particularly obvious at the lower layers (i.e., physical and data link layer, with the latter in CCSDS including data link protocol sublayer and synchronization and channel coding sublayer). Table 2 shows a sample of the frequency bands, modulation and coding schemes, and space data link layer protocols that reflect the mission use cases in the current paradigm.

Table 2 A Sample of Frequency, Modulation, Coding, and Link Protocol in Current Paradigm

Source/Destination	Frequency Bands	Modulation	Coding	Link Layer
Earth to Moon	2025-2110 MHz 7190-7235 MHz	PCM/PM/bi-phase-L; PCM/PM/BPSK; PM/PSK/NRZ	BCH; LDPC	TC; AOS
Moon to Earth	2200-2290 MHz 8450-8500 MHz 25.5-27.0 GHz	PCM/PSK/PM BPSK; QPSK; GMSK; OQPSK, SQPSK	Concatenated (Convolutional + Reed-Solomon); Turbo; LDPC; Convolutional code only	TM; AOS
Cross-Link	N/A	N/A	N/A	N/A
Proximity-Link (towards lunar surface)	390-405 MHz	PCM/PM/bi-phase-L	Convolutional	Proximity -1
Proximity-Link (away from lunar surface)	435-450 MHz	PCM/PM/bi-phase-L	Convolutional	Proximity -1
Lunar Surface to Lunar Surface	N/A	N/A	N/A	N/A

As part of an IOAG effort back in 2016, a Lunar mission data sheet was constructed to capture all the communication link parameters and services for all the Lunar missions. The data sheet has been further updated to include the information for those missions recently planned by the various international Lunar exploration forums, e.g., ISECG, ISS-partnership, and Lunar Gateway/Transport program. Table 3 contains an extracted set of the communication link parameters and services for the Lunar missions launched and to be Launched during the timeframe of 2018 – 2030.

Table 3 Lunar Missions (Launch During 2018-2030) – Communications Link Parameters and Services

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets ♪	Frequencies			Modulation standards	Coding standards	IOAG Standard Services¥				IOAG Standard Services¥¥		Relay Services	Navigation Services
							Uplink frequencies	Downlink frequencies	Crosslink or Proximity link frequencies			Forward Data Delivery Services	Return Data Delivery Services	Radio Metric Services	Monitor Dara Service	Space Internet-working Service	File/ Messaging Service		
Chandrayaan-2	2019	ISRO	3	Orbiter, S . Pole Farside Lander/rover	NASA	IDSN, DSN	S-band	S-band, X-band	S-band: orbiter - lander; S-band: rover - lander	•PCM/PSK/PM: S-band uplink; •BPSK: S-band downlink; •QPSK: X-band downlink;	R/S-Conv. Concat; Turbo	FCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	[TBD]	No	No	Proximity-1 [TBC]	[TBD]
Chandrayaan-3	2022	ISRO	2	S. Pole far-side lander/rover	NASA	IDSN, DSN	S-band	S-band, X-band	S-band: orbiter - lander; S-band: rover - lander	•PCM/PSK/PM: S-band uplink; •BPSK: S-band downlink; •QPSK: X-band downlink;	R/S-Conv. Concat; Turbo	FCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	[TBD]	No	No	Proximity-1 [TBC]	[TBD]
Chang'e 4	2018	CNSA	3	Orbiter, S. Pole Farside Lander/rover	ESA	Kashgar, Jiamusi, Miyun, & Neuquén (Argentina), ESA DSN	S-band	S-band	X-band	TTC:PCM/PSK/PM	R/S-Conv. concat	PCM	PCM	Delta DOR Service	[TBD]	[TBD]	[TBD]	DC downlink:X-band,1Mbit/s TT&C uplink:X-band,1000bit/s TT&C downlink:X-band,2048bit/s	[TBD]
Chang'e 5	2020	CNSA	4	Orbiter/lander/ascender/sample return capsule	ESA	Kashgar, Jiamusi, Miyun, & Neuquén (Argentina)	X-band	X-band	Ka:5kbit/s Ku:5kbit/s	TTC:PCM/PSK/PM; DC downlink:BPSK	R/S-Conv. concat	Forward CLTU Service	Return All Frames Service	Delta DOR Service	[TBD]	[TBD]	[TBD]	——	[TBD]
Chang'e 6	2024	CNSA	4	Orbiter/lander/ascender/sample return capsule	ESA	Kashgar, Jiamusi, Miyun, & Neuquén (Argentina)	X-band	X-band	Ka:5kbit/s Ku:5kbit/s	TTC:PCM/PSK/PM; DC downlink:BPSK	R/S-Conv. concat	Forward CLTU Service	Return All Frames Service	Delta DOR Service	[TBD]	[TBD]	[TBD]	——	[TBD]
Chang'e 7*	2024	CNSA	3	Orbiter/lander/rover S. Pole research station	Cosrosmos, ESA	Kashgar, Jiamusi, Miyun, & Neuquén (Argentina)	X-band	X-band	Ka:5kbit/s Ku:5kbit/s	TTC:PCM/PSK/PM; DC downlink:BPSK	R/S-Conv. concat	Forward CLTU Service	Return All Frames Service	Delta DOR Service	[TBD]	[TBD]	[TBD]	——	[TBD]
Chang'e 8*	2027	CNSA	2	Lander/rover/flying detector for S. Pole in-situ resource utilization	Cosrosmos, ESA	Kashgar, Jiamusi, Miyun, & Neuquén (Argentina)	X-band	X-band	Ka:5kbit/s Ku:5kbit/s	TTC:PCM/PSK/PM; DC downlink:BPSK	R/S-Conv. concat	Forward CLTU Service	Return All Frames Service	Delta DOR Service	[TBD]	[TBD]	[TBD]	——	[TBD]
Beresheet Lander	2019	SpaceIL	1	Small lander	NASA, DLR	DSN, DLR station	X-band	X-band	None	CCSDS	CCSDS	FCLTU Service	RAF Service	[TBD]	[TBD]	[TBD]	[TBD]	None	[TBD]

Table 3 Continued

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets ♪	Frequencies			Modulation standards	Coding standards	IOAG Standard Services¥				IOAG Standard Services¥¥		Relay Services	Navigation Services
							Uplink frequencies	Downlink frequencies	Crosslink or Proximity link frequencies			Forward Data Delivery Services	Return Data Delivery Services	Radio Metric Services	Monitor Dara Service	Space Internet-working Service	File/ Messaging Service		
Beresheet-2 Lander*	[TBD]	SpaceIL	3	Orbiter and 2 landers	[TBD]	DSN, DLR station	X-band	X-band	None	CCSDS	CCSDS	FCLTU Service	RAF Service	[TBD]	[TBD]	[TBD]	[TBD]	None	[TBD]
Korea Pathfinder Lunar Orbiter (KPLO)	2022	KARI	1	Orbiter	NASA	KDSA, DSN	S-band	S-band, X-band	None	PCM/PSK/PM, BPSK, OQPSK, GMSK [TBC]	R/S-Conv. Concat	FCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	[TBD]	DTN BP (experiment only)	CFDP (experiment only)	None	[TBD]
Korean Lunar Mission Phase 2	2020s	KARI	3	Orbiter/lander/rover	[TBD]	KDSA and other assets	S-band	S-band, X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	——	[TBD]
Luna-25 Lander	2022	Roscosmos	1	Lander on S. Pole	ESA	RFSA Network	C-band: up to 1 Kbits/s	C-band: up to 32 Kbit/s	None	BPSK: suppressed & residual carriers	R/S-Conv. Concat	TC-DLP	TM-DLP	RFM	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
Luna-26 Orbiter	2024	Roscosmos	1	Orbiter	ESA	RFSA Network	C-band: up to 1 Kbits/s	C-band: up to 32 Kbit/s	UHF: up to 256 kbits/s	BPSK: suppressed & residual carriers	Conv.	TC-DLP	TM-DLP	RFM	[TBD]	[TBD]	[TBD]	Proximity-1	[TBD]
Luna-27 lander*	2026	Roscosmos	1	Lander on S. Pole	ESA	RFSA Network	C-band: up to 1 Kbits/s	C-band: up to 32 Kbit/s	UHF: up to 256 kbits/s	BPSK: suppressed & residual carriers	Conv.	TC-DLP	TM-DLP	RFM	[TBD]	[TBD]	[TBD]	Proximity-1	[TBD]
Luna-28*	2027	Roscosmos	2	Lander on S. Pole & sample return	ESA	RFSA Network	C-band: up to 1 Kbits/s	C-band: up to 32 Kbit/s	UHF: up to 256 kbits/s	BPSK: suppressed & residual carriers	Conv.	TC-DLP	TM-DLP	RFM	[TBD]	[TBD]	[TBD]	Proximity-1	[TBD]
Luna-29*	2028	Roscosmos	1	Rover on S. Pole	[TBD]	RFSA Network	C-band: up to 1 Kbits/s	C-band: up to 32 Kbit/s	UHF: up to 256 kbits/s	BPSK: suppressed & residual carriers	Conv.	TC-DLP	TM-DLP	RFM	[TBD]	[TBD]	[TBD]	Proximity-1	[TBD]
Smart Lander for Investigating Moon (SLIM)	2021	JAXA	1	Lander	None	JAXA Network	S-band	S-band	None	CCSDS	CCSDS	None	None	None	[TBD]	[TBD]	[TBD]	None	[TBD]
Commercial Lunar Payload Services (CLPS)	2020~2028	NASA/ Industry	10	Small landers with NASA payloads	[TBD]	DSN/NSN, relay	X-band	X-band	S-band	PCM/PM/NRZ-L, Residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric	Monitor Data-CSTS	[TBD]	[TBD]	[TBD]	[TBD]
Cislunar Autonomous Positioning System Technology Operations & Navigation (CAPSTONE)	2021	NASA	1	CubeSat orbiter for technology demo	None	DSN, MSU	X-band	X-band	None	PCM/PM/NRZ-L, Residual carrier	Uplink: convolutional code, rate 1/2; Downink: R/S-Conv. Concat	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	None	None	None	None
Lunar Node-1	2022	NASA	1	Lunar orbiter	None	DSN	X-band	X-band	None	PCM/PM/NRZ-L, Residual carrier	Uplink: convolutional code, rate 1/2; Downink: R/S-Conv. Concat	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	None	None	None	None

Table 3 Continued

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets ♪	Frequencies			Modulation standards	Coding standards	IOAG Standard Services¥				IOAG Standard Services¥¥		Relay Services	Navigation Services
							Uplink frequencies	Downlink frequencies	Crosslink or Proximity link frequencies			Forward Data Delivery Services	Return Data Delivery Services	Radio Metric Services	Monitor Dara Service	Space Internet-working Service	File/ Messaging Service		
PRIME-1	2022	NASA	1	Lunar orbiter	None	DSN	X-band	X-band	None	PCM/PM/NRZ-L, Residual carrier	Uplink: convolutional code, rate 1/2; Downink:	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	None	None	None	None
Volatile Investigating Polar Exploration Rover (VIPER)	2023	NASA	1	Rover	None	DSN	X-band	X-band	None	PCM/PM/NRZ-L, Residual carrier	Uplink: LDPC, rate 1/2; Downlink: LDPC rate 1/2	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	None	None	None	None
Lunar Communications Pathfinder	2024	Goonhilly, SSTL, UKSA	1	Relay Orbiter	ESA	Goonhilly station, ESA DSN	X-band	X-band	S-band and UHF	PCM/PM/NRZ-L, Residual carrier	LDPC, rate 1/2	FCLTU Service	RAF/RCF Services	[TBD]	[TBD]	None	[TBD]	Proximity-1	[TBD]
Lunar TrailBlazer	2025	NASA	1	SmallSat orbiter	None	DSN, MSU	X-band	X-band	None	PCM/PM/NRZ-L, Residual carrier	Uplink: convolutional code, rate 1/2; Downink: R/S-Conv. Concat	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	None	None	None	None
Lunar Terrain Vehicle (LTV)	2025	NASA	1	Lunar surface	[TBD]	DSN	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
Lunar Gateway – Power Propulsion Element (PPE) + Habitation & Logistics Outpost (HALO)	2025	NASA	1	Orbiter in Near-Rectilinear Halo Orbit (NRHO)	ESA, JAXA, CSA	DSN, NSN, ESA DSN	X-band, K-band	X-band, K-band	UHF with EVA; S-and K-Band with relay users; S-band with VV	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Lunar Polar Exploration (LUPEX)	2025	JAXA/ISRO	2	Lunar rover and lander in S. Pole	NASA	IDSN, JAXA network, DSN	X-band	X-band	S-band: Lander-rover	CCSDS	CCSDS	FCLTU Service	RAF Service	[TBD]	[TBD]	[TBD]	[TBD]	None	[TBD]
Lunar Relay Network	2024	NASA	3	Relay orbiters in 12-hour frozen orbit	Commercial	DSN, NSN, ESA DSN	X-band, K-band	X-band, K-band	S-and K-Band with relay users;	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Lunar Gateway – International Habitation Module (I-Hab)	2025	ESA, JAXA	1	NRHO	ESA, JAXA, CSA	DSN, NSN, ESA DSN	X-band, K-band	X-band, K-band	S-and K-Band with relay users;	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
ISRU Demo	2026	NASA	1	Lunar surface	[TBD]	DSN, NSN	X-band, K-band	X-band, K-band	S-band	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Lunar Gateway – European System Providing Refueling. Infrastructure & Telecommunications (ESPRIT)	2027	ESA	1	NRHO	ESA, JAXA, CSA	DSN, NSN, ESA DSN	X-band, K-band	X-band, K-band	S-and K-Band with relay users;	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]

Table 3 Continued

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets ♪	Frequencies			Modulation standards	Coding standards	IOAG Standard Services ¥				IOAG Standard Services ¥¥		Relay Services	Navigation Services
							Uplink frequencies	Downlink frequencies	Crosslink or Proximity link frequencies			Forward Data Delivery Services	Return Data Delivery Services	Radio Metric Services	Monitor Dara Service	Space Internet-working Service	File/ Messaging Service		
Exploration Command Module (ECM)	2027	NASA	1	NRHO	ESA, JAXA, CSA	DSN, NSN, ESA DSN	X-band, K-band	X-band, K-band	S-and K-Band with relay;	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Taiwan Lunar Science Orbiter*	2025	NSPO	1	SmallSat Orbiter	[TBD]	DSN [TBD]	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	DTN BP/LTP	[TBD]	[TBD]	[TBD]
Gateway Logistics Services (GLS-1 thru GLS-7)	2025 - 2031	NASA	7	Transit to NRHO orbit	ESA, JAXA, CSA	DSN, NSN	X-band	X-band	S-band	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	[TBD]	AOS over Proximity-1;	[TBD]
Habitable Mobility Platform (HMP)	2028	NASA/JAXA	1	Cargo lander	ESA, JAXA, CSA	DSN, NSN, ESA DSN, JAXA network	X-band	X-band	S-and K-Band with relay	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Foundational Surface Habitat (FSH)	2029	NASA	1	Cargo lander	ESA, JAXA, CSA	DSN, NSN, ESA DSN, JAXA network	X-band	X-band	S-and K-Band with relay	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Geophysical Network	2030	NASA	2	Orbiter and Lander	[TBD]	DSN, NSN	X-band	X-band	S-band	PCM/PM/bi-phase-L; residual carrier	LDPC rate ½	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	[TBD]	AOS over Proximity-1;	[TBD]
Fission Surface Power	2029	NASA	1	Lunar S. Pole	[TBD]	DSN, NSN	X-band	X-band	S-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
ISRU Pilot Plant	2029	ESA	1	Lunar S. Pole	[TBD]	ESA DSN	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
EL3 (European Large Logistic Lander) Mission 1	2029+	ESA	1 or 2	Lander with cargo and/or scientific payload (including potentially mobile element)	[TBD]	ESA DSN, Lunar reway (TBC)	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
CLTV (Cis Lunar Transfer Vehicle) Mission 1	2027+	ESA	1	Multi-purpose (cargo , refuelling) transfer vehicle to lunar orbit	ESA	ESA DSN	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
VMMO (Volatile and Mineralogy Orbiter)	202x	ESA	1	Cubesat	[TBD]	Lunar Pathfinder[TBC] or ESA DSN	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
LUMIO (Lunar Meteroid Impacts observer)	202x	ESA	1	Cubesat	[TBD]	Lunar Pathfinder[TBC] or ESA DSN	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
Moonlight / LCNS	2026-2027	ESA	3+ (TBC)	Lunar Communications and Navigation Service	[TBD]	[TBD]	X-band	X-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
Pressurized Crewed Rover	2029	JAXA	1	Lunar S. Pole	[TBD]	[TBD]	X-band, optical	X-band, optical	S-and K-Band with relay	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]

Table 3 Continued

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets ♪	Frequencies			Modulation standards	Coding standards	IOAG Standard Services¥				IOAG Standard Services¥¥		Relay Services	Navigation Services
							Uplink frequencies	Downlink frequencies	Crosslink or Proximity link frequencies			Forward Data Delivery Services	Return Data Delivery Services	Radio Metric Services	Monitor Dara Service	Space Internet-working Service	File/ Messaging Service		
Transit Habitat	2030	NASA	1	Lunar surface	ESA, JAXA, CSA	DSN, NSN, ESA DSN, JAXA network	X-band	X-band	S-and K-Band with relay	PCM/PM/bi-phase-L; residual carrier	LDPC rates ½, 2/3, 4/5	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	None	DTN BP/LTP	CFDP, AMS	AOS over Proximity-1;	[TBD]
Artemis-1/Orion	2022	NASA	1	Orbiter in Distant Retrograde Obit (DRO)	SANSA, JAXA	DSN,, Hartebeesthoek (HBK), JAXA Network [TBD]	S-band	S-band	None	•PCM/PM/NRZ: S-band uplink; •PCM/PM/NRZ, SQPSK: S-band downlink;	•LDPC: uplink; •LDPC: downlink	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	Monitor Data-CSTS	No	[TBD]	None	[TBD]
Artemis-2/Orion	2023	NASA	1	Orbiter	SANSA, JAXA [TBD]	DSN, Hartebeesthoek (HBK), JAXA Network [TBD]	S-band	S-band	None	•PCM/PM/NRZ: S-band uplink; •PCM/PM/NRZ, SQPSK: S-band downlink;	•LDPC: uplink; •LDPC: downlink	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	Monitor Data-CSTS	DTN BP/LTP	[TBD]	None	[TBD]
Artemis-3/Orion	2024	NASA	1	Orbiter	[TBD]	DSN/NSN, Lunar Gateway	S-band	S-band	None	•PCM/PM/NRZ: S-band uplink; •PCM/PM/NRZ, SQPSK: S-band downlink;	•LDPC: uplink; •LDPC: downlink	EFCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	Monitor Data-CSTS	DTN BP/LTP	[TBD]	None	[TBD]
Artemis-3/Human Landing System (HLS)	2025	NASA	3	HLS: descent, ascent, & transfer modules	[TBD]	DSN/NSN, Lunar Gateway	S-band	S-band	S-band, K-band	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
Artemis-4*, -5*, -6*, -7*	2025-2030	NASA	16	Orion and HLS (descent, ascent, transfer modules)	[TBD]	DSN/NSN, Lunar Gateway	For Orion, the same as that for Artemis-1/Orion. For HLS, the same as that for Artemis-3/HKS.												
Lunar Flashlight	2023	NASA	1	CubeSat Orbiter	ESA [TBD], JAXA [TBD]	DSN, MSU	X-band	X-band	None	•PM/PSK/NRZ: X-band uplink; •PSK: X-band downlink	Turbo	FCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	Monitor Data-CSTS	[TBD]	[TBD]	None	[TBD]
Lunar IceCube	2022	NASA	1	CubeSat Orbiter	ESA [TBD], JAXA [TBD]	DSN, MSU	X-band	X-band	None	•PM/PSK/NRZ: X-band uplink; •PSK: X-band downlink	Turbo	FCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	Monitor Data-CSTS	DTN BP	[TBD]	None	[TBD]
LunaH-Map	2022	NASA	1	CubeSat Orbiter	ESA [TBD], JAXA [TBD]	DSN, MSU	X-band	X-band	None	•PM/PSK/NRZ: X-band uplink; •PSK: X-band downlink	Turbo	FCLTU Service	RAF/RCF Services	Validated Data Radio Metric Services	Monitor Data-CSTS	[TBD]	[TBD]	None	[TBD]
ArgoMoon	2022	ASI	1	CubeSat Orbiter	NASA	Sardinia DSA, DSN (i.e. Goldstone, Madrid, Canberra)	X-band	X-band	None	PCM/PSK/PM,NRZ	Turbo, Manchester, R/S-Conv. Concat	FCLTU Service	RAF Service	Validated Data Radio Metric Service	[TBD]	[TBD]	[TBD]	None	[TBD]
Omotenashi	2022	JAXA	1	CubeSat Lander	NASA	JAXA Network, DSN [TBD]	X-band [TBD]	X-band [TBD]	None	CCSDS	CCSDS	FCLTU Service	RAF/RCF Services	[TBD]	[TBD]	[TBD]	[TBD]	None	[TBD]
Equuleus	2022	JAXA	1	CubeSat Orbiter	NASA	JAXA Network, DSN [TBD]	X-band	X-band	None	CCSDS	CCSDS	FCLTU Service	RAF Service	[TBD]	[TBD]	[TBD]	[TBD]	None	[TBD]

Table 3 Continued

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communication assets ♪	Frequencies			Modulation standards	Coding standards	IOAG Standard Services¥				IOAG Standard Services¥¥		Relay Services	Navigation Services
							Uplink frequencies	Downlink frequencies	Crosslink or Proximity link frequencies			Forward Data Delivery Services	Return Data Delivery Services	Radio Metric Services	Monitor Dara Service	Space Internet-working Service	File/ Messaging Service		
Cislunar Explorer	2022	NASA	1	Artemis-1 co-manifest CubeSat orbiter	None	DSN, MSU	X-band	X-band	None	CCSDS	CCSDS	FCLTU Service	RAF Service	[TBD]	[TBD]	[TBD]	[TBD]	None	[TBD]
Lunar InfraRed Imaging (LunIR)	2022	NASA	1	Artemis-1 co-manifest CubeSat orbiter	DoD	AFSCN	X-band	X-band	None	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
Artemis-2 thru -8* CubeSat/SmallSat	2022-2028	NASA	TBD	Artemis co-manifest CubeSat/ SmallSat orbiters/landers	[TBD]	DSN/NSN, MSU	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]
SkyMage	2023	US Air Force Labs	1	CubeSat Orbiter	None	Commercial stations	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]

<u>Footnotes:</u>

*Proposed mission or mission concept in planning.
¥ Services defined in IOAG Service Catalog 1.
¥¥ Services defined in IOAG Service Catalog 2.
♪ Ground station, network, or relay orbiter.

- X-band: When used for DTE/DFE links, it refers to near Earth X-band allocation, i.e., 7190-7235 MHz for uplink and 8450-8500 MHz for downlink.
- S-band: Refers to near Earth S-band allocation, i.e., 2025–2110 MHz for uplink and 2200–2290 MHz for downlink
- UHF-band: Refers to 435 to 450 MHz for return link and 390 to 405 MHz for forward link."

<u>Color codes for cell fills:</u>

Gray: Currently flying or past missions.
Green: Phase-1 missions (2021-2025).
Orange: Phase-2 missions (2025 -2030).
Blue: Cubesat/Smallsat as co-manifested payload for Artemis launch vehicle

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Findings and observations based on the communication link information shown in Table 3 are as follows:

- At physical layer, for Moon-to/from-Earth TT&C links, divergence in frequency bands continues to exist. Both S- and X-bands will co-exist during this period although X-band is gaining popularity among lunar missions.
- For Moon-to/from-Earth high-rate communications, Ka-band and/or optical links are beginning to happen.
- At least 4 missions will provide relay capability. However, the frequency band(s) for proximity links are yet to converge.
- For high-rate proximity link, only one mission plans to operate Ka-band and/or optical links.
- Modulation schemes, although too many, are all CCSDS-compliant and largely consistent with the "IOAG Report on Preferred Coding and Modulation Schemes".
- Bandwidth efficient modulation, e.g., GMSK, has not been very popular even for the more congested S- and X-bands. Perhaps, this is because most are not “high-rate” missions demanding high spectral efficiency.
- Coding schemes are more confined to traditional codes:
  - Reed-Solomon/convolutional concatenated code for downlink
  - BCH code for uplink

  But higher performance codes, i.e., LDPC and Turbo codes, are emerging for lunar communications.
- The use of high-performance coding schemes for Earth-to-Moon uplink is happening.
- The use of high-performance coding schemes for proximity link is imminent. But for the next few years, the convolutional code per the CCSDS Proximity-1 standard is still the most dominant scheme.
- The provision of standard services per IOAG Service Catalog-1 v2.0 (except Relay Services) for inter-agency cross support purpose has been universally accepted by all lunar missions.
- The provision of Lunar relay services, in an end-to-end sense (i.e., encompassing the direct Earth and proximity links), by the various planned relay missions remains dissimilar.
- Among the 4 missions offering relay links, only the Lunar Communications Pathfinder and Lunar Gateway are explicitly planned to offer relay services for inter-agency cross support purpose.
- A Lunar Network will come into fruition during this decade.
- Lunar Communications Pathfinder may become the first relay orbiter with relay communications as its primary mission objective.

3.2. Key Considerations for Down-Selection

Since a major international drive is being undertaken to capture the communications requirements for the Lunar Gateway program, given the fact that the Lunar Gateway represents a superset mission instance for almost all types of Lunar missions, it is reasonable to apply the Lunar Gateway communications architecture (physical and data link layers) we proposed in January 2018 to that for the future Lunar communication architecture. A key objective in that Lunar Gateway effort is to achieve highest degree of interoperability among all communication assets of all participating agencies and companies. Driven by the need for interoperability among future Lunar missions, including Lunar Gateway and Lunar surface science missions, it's been recognized that the set of CCSDS standards are key to the design of the Lunar space communications architecture. However, the rich repertoire of the standards produced and evolved by the CCSDS over the years is a curse as well as a blessing – there are too many standards to choose from:

- The multitude of signal formats, modulation and coding schemes can be an impediment for interoperability, let alone a cost driver for future missions.
- The divergence of space data link protocols, being unduly dependent on link directionality, link type, and even link rate (low-rate vs. high-rate link), would become a serious problem for the international Lunar campaign as currently being devised by the ISECG.

Therefore, it's imperative for us to pick and choose the suitable standards as the solutions to the future Lunar communications architecture.

Table 4 summarizes the down-selected standards for the physical and data link layers of the Lunar communications architecture. They have largely been adopted by the Lunar Gateway in one of its interoperability requirement documents, i.e., the International Communication System Interoperability Standards (ICSIS). The down-selection of frequency bands, modulation and coding schemes, ranging approaches and space data link protocols are based on the following considerations:

- Interoperability between Lunar space vehicles (both orbital and surface-based) and Earth stations
- Interoperability between Lunar relay orbiters and their user vehicles (both orbital and surface-based)
- Costs of implementation
- Constraints due to spectral limitation: ITU, SFCG and NTIA imposed

3.3. Down-selection of Frequency Bands, Modulation and Coding Schemes, Ranging Methods, and Space Data Link Protocols

The communication standards identified in Table 4 are organized according to the various types of link that will exist in the future Lunar communications architecture. These link types are defined as follows:

- **Earth-to-Moon:** *The uplink from the Earth to cis-lunar, lunar orbit and lunar surface.*
- **Moon-to-Earth**: *The downlink from the cis-lunar, lunar orbit and lunar surface to the Earth.*
- **Cross Link**: *The link between two relay spacecraft*.
- **Proximity Link**: *The link between a relay satellite and its relay service user. Relay service users can be orbital spacecraft, descent/ascent vehicles, lander, rovers, and, potentially, astronauts equipped with portable communication device, communication stations/towers on surface, and human habitats. The relay satellites have the potential to broadcast downlink signals for Position, Navigation and Timing (PNT) systems*
- **Lunar Surface to Lunar Surface**: *The communications between a landed asset and a landed asset.*

Source/Destination	Frequency Bands[1]	Modulation[2]	Coding[3]	Space Data Link Protocol	Space Link Security	Ranging
Earth to Moon	RF – low rate: 7190-7235 MHz	Nominal				
		• Option 1: PCM/PM/bi-phase-L - Modulation on residual carrier • Option 2: GMSK with PN	LDPC[8,3,12]: Coding rates – ½, 2/3, 4/5, 7/8 BCH[12] (Recommended for low uplink rate missions only)	AOS[6], USLP[7] TC[14] Recommended for low uplink rate missions only	• CCSDS Space Data Link Security Protocol[11], • CCSDS Cryptographic Algorithms[31]	CCSDS PN[9] • Non-regenerative for Modulation Option 1. • Regenerative for Modulation Option 2. • Ranging chip rate: 4 Mcps. • Simultaneous data and PN ranging for both modulation options.
		Spacecraft special event/emergency/contingency				
		• PCM/PSK/PM - Modulation on subcarrier	• Option 1- BCH[12] • Option 2 – LDPC[8,3,12] Codeword size – 128 octets (for LDPC rate ½)	AOS[6], USLP[7]	(Same as above)	CCSDS PN[9] • Non-regenerative. • Ranging chip rate: 2 Mcps
	RF – high rate: 22.55-23.15 GHz	Nominal				
		• Filtered OQPSK/ GMSK - Modulation on suppressed carrier	LDPC [8, 3, 12] Coding rates – ½, 2/3, 4/5, 7/8 CCSDS VCM (DVB-S2, SCCC, or LDPC-VCM) to be selected for higher rates and higher coding performance.	AOS[6], USLP[7]	• CCSDS Space Data Link Security Protocol[11], • CCSDS Cryptographic Algorithms[31]	For links ranging is needed: CCSDS PN[9] • GMSK with simultaneous data and PN ranging
	Optical: 1550 nm[4]	PPM[4]	SCPPM[5]	AOS[6], USLP[7]	(Same as above)	None
Moon to Earth	RF – low rate: 8450-8500 MHz	Nominal				
		• Option 1: PCM/PM/bi-phase-L - Modulation on residual carrier • Option 2: GMSK with PN	LDPC[3] Coding rates – ½, 2/3, 4/5, 7/8	AOS[6], USLP[7] USLP with slicing TM[18] Recommended for low downlink rate missions only	• CCSDS Space Data Link Security Protocol[11], • CCSDS Cryptographic Algorithms[31]	CCSDS PN[9] • Non-regenerative for Modulation Option 1. • Regenerative for Modulation Option 2.

						• Ranging chip rate: 4 Mcps. • Simultaneous data and PN ranging for both modulation options.
		Spacecraft special event/emergency/contingency				
		• PCM/PSK/PM - Modulation on subcarrier	• Option 1 – Concatenated (Convolutional + Reed-Solomon[3] • Option 2 – LDPC[3] Codeword size – 128 octets (for LDPC rate ½)	AOS[6], USLP[7] USLP with slicing	• CCSDS Space Data Link Security Protocol[11], • CCSDS Cryptographic Algorithms[31]	CCSDS PN[9] • Non-regenerative. • Ranging chip rate: 2 Mcps
	RF – high-rate: 25.5-27.0 GHz	Nominal				
		• Filtered OQPSK/ GMSK - Modulation on suppressed carrier	LDPC[3] Coding rates – ½, 2/3, 4/5, 7/8 CCSDS VCM (DVB-S2, SCCC, or LDPC-VCM) to be selected for higher rates and higher coding performance.	AOS[6], USLP[7] USLP with slicing	• CCSDS Space Data Link Security Protocol[11], • CCSDS Cryptographic Algorithms[31]	For links ranging is needed: CCSDS PN[9] • GMSK with simultaneous data and PN ranging
	Optical: 1550 nm[4]	PPM[4]	SCPPM[5]	AOS[6], USLP[7]	(Same as above)	None
Cross-Link (Relay-other relay orbiters)	23.15-23.55 GHz 27.0-27.5 GHz	• Filtered OQPSK/ GMSK - Modulation on suppressed carrier	LDPC[8,3] Coding rates – ½, 2/3, 4/5, 7/8 CCSDS VCM (DVB-S2, SCCC, or LDPC-VCM) to be selected for higher rates and higher coding performance.	AOS[6], USLP[7] USLP with slicing	(Same as above)	For links ranging is needed: CCSDS PN[9] • GMSK with simultaneous data and PN ranging
	Optical: 1550 nm[4]	PPM[4]	SCPPM[5]	AOS[6], USLP[7]	(Same as above)	None
Proximity-Link (Relay to lunar surface or user orbiter)	RF – low rate: 2025-2110 MHz RF - low rate: 2483.5 -2500 MHz	Option 1 – PCM/PM/bi-phase-L • Modulation on residual carrier (for FDMA);	LDPC[8,3] Coding rates – ½, 2/3, 4/5, 7/8 Convolutional Code[16]: (Recommended only for low	USLP[7] USLP with slicing Proximity -1[17]:	(Same as above)	Option 1 – CCSDS PN[9] (for residual carrier) • Non-regenerative for Modulation Option 1.

	RF- Low Rate: 390 – 405 MHz (UHF is limited to and from the lunar surface. Orbit to orbit and use around the "Shielded Zone" of the Moon is not allowed[1]).	Option 2 – CDMA[10]	rate missions not using Lunar Gateway for relay)	(Recommended only for low rate missions not using Lunar Gateway for relay)		• Regenerative for Modulation Option 2. • Ranging chip rate: 4 Mcps. • Simultaneous data and PN ranging for both modulation options. Option 2 – CCSDS PN[10] (for CDMA link) • CCSDS PN patterns will be augmented with SN PN patterns to support visiting vehicles like Artemis-2.
	RF- high rate: 23.15 – 23.55GHz	• Filtered OQPSK/ GMSK - Modulation on suppressed carrier	LDPC[8,3] Coding rates – ½, 2/3, 4/5, 7/8 CCSDS VCM (DVB-S2, SCCC, or LDPC-VCM) to be selected for higher rates and higher coding performance.	USLP[7] USLP with slicing	(Same as above)	For links ranging is needed: CCSDS PN[9] • GMSK with simultaneous data and PN ranging
	Optical: 1550 nm[4]	PPM[4]	SCPPM[5]	USLP[7]	(Same as above)	None
Proximity-Link (lunar surface or user orbiter to Relay)	RF – low rate: 2200-2290 MHz RF- Low Rate 435-450 MHz (UHF is limited to and from the lunar surface. Orbit to orbit and use around the "Shielded Zone" of the Moon is not allowed[1]).	Option 1 – PCM/PM/bi-phase-L • Modulation on residual carrier (for FDMA); Option 2 – CDMA[10]	LDPC[3] Coding rates – ½, 2/3, 4/5, 7/8 Convolutional Code [16]: (Recommended only for low rate missions not using Lunar Gateway for relay)	USLP[7] USLP with slicing Proximity-1 [17] (Recommended only for low rate missions not using Lunar Gateway for relay)	(Same as above)	Option 1 – CCSDS PN[9] (for residual carrier) • Non-regenerative • for Modulation Option 1. • Regenerative for Modulation Option 2. • Ranging chip rate: 4 Mcps. • Simultaneous data and PN ranging for

						both modulation options. Option 2 – CCSDS PN[10] (for CDMA link) • CCSDS PN patterns will be augmented with SN PN patterns to support visiting vehicles like Artemis-2.
	RF- high rate: 27.0 – 27.5 GHz	• Filtered OQPSK/ GMSK - Modulation on suppressed carrier	LDPC[3] Coding rates – ½, 2/3, 4/5, 7/8 CCSDS VCM (DVB-S2, SCCC, or LDPC-VCM) to be selected for higher rates and higher coding performance.	USLP[7] USLP with slicing	(Same as above)	For links ranging is needed: CCSDS PN[9] • GMSK with simultaneous data and PN ranging
	Optical: 1550 nm[4]	PPM[4]	SCPPM[5]	AOS[6], USLP[7]	(Same as above)	None
Lunar Surface to Lunar Surface (access point based networks – same allocation can be used for direct client-to-client communications)	Frequency allocations* currently foreseen by SFCG[1] 390-405 MHz 410-420 MHz 435-450 MHz 2.4-2.48 GHz 25.25-25.60 GHz 27.225-27.5 GHz	Depending on scenario (ref. section 4.4): IEEE 802.11[13] 3GPP LTE[43] 3GPP 5G[44]	Depending on scenario (ref. section 4.4): IEEE 802.11[13] 3GPP LTE[43] 3GPP 5G[44]	Depending on scenario (ref. section 4.4): IEEE 802.11[13] 3GPP LTE[43] 3GPP 5G[44]	IEEE 802.11[13] 3GPP LTE[43] 3GPP 5G[44]Security	None

Table 4. Down-Selected Standards for the Physical and Data Link Layers of the Lunar Communications Architecture

[**Note: The set of frequency allocations for surface-to-surface communications may require extension with the introduction of 3GPP technology and latest 802.11 developments and with the consideration of the Radio Regulation applicable in the Shielded Zone of the Moon* [40][42].]

3.4. Key Issues:

Throughout the down-selection process, key issues were identified along the way. The following covers the description of these issues and some relevant discussions -

Issue 1. Earth-to-Moon high-rate link:

We suggested 22 GHz Ka-band for Earth-to-Moon high-rate link be included in the Lunar communications architecture for this era. We understand that the highest data rate for any mission is about 10 Mbps, as currently identified for the Lunar Gateway Power Propulsion Element (PPE). However, for crewed missions to the Moon, we do not consider it will be truly sufficient for the human Lunar exploration era. Note: Given the fact that the ISS called for 25 Mbps in 2013, it is hard to believe that 10 Mbps would be sufficient in +2022 era.

Issue 2. Moon-to-Earth and Earth-to-Moon high-rate links: 37-38 GHz and 40-41 GHz bands

Recognizing the potential interference with the same Ka-band used for high-rate proximity links, the use of 37-38 GHz and/or 40-41 GHz bands for Moon-to-Earth and Earth-to-Moon, respectively, would be ideal:

a. Argument for:

- RFI-free in the long term, increased operability.
- Both bands would allow "seamless" transition of human exploration vehicles from the Earth to Moon to Mars.

b. Argument against:

- High implementation costs for adding this capability to the Earth stations and the RF terminal on-board the orbiters.
- RFI with proximity high-rate links and other missions could be avoided and mitigated through coordinated allocations. Since the maximum data rate for the Moon-to-Earth link is 100 Mbps, given the 1.5 GHz total bandwidth this may not be a serious problem.
- If the 22 GHz/26 GHz bands indeed become congested, it is about time for some high-rate missions to move to optical. These high-rate missions, e.g., Lunar Gateway, should have optical communications for both Lunar proximity and Moon-Earth links.

c. Since we have little insight about the cost posture of the future high-rate missions and no cost/performance trade-off has been done for this issue, our decision of excluding the 37-38 GHz and/or 40-41 GHz bands at this time should be treated as a tentative, point decision.

Issue 3. Earth-to-Moon low-rate link - Modulation:

With only 45 MHz worth of spectrum available in total for Category A space, we have two options for modulation on this link:

a. Conventional PCM scheme on residual carrier: It works, but may not be a long term solution for an era when there are many lunar missions competing for the limited bandwidth. Its effect must be analyzed deeper. At a minimum, the SFCG has to assess X-band channel allocations on the uplink to all user missions.
b. Bandwidth-efficient modulation scheme: GMSK for simultaneous data and PN ranging gives is a good solution. This is a new capability as standardized in the new CCSDS RF and Modulation blue book. The approach should be close enough for ensuring high spectral efficiency for lunar communication links where power efficiency might not matter very much. But, then, both lunar spacecraft and Earth stations would have to upgrade to handle this scheme. Again, a cost item.

Issue 4. Spacecraft emergency links - Coding:

Coding schemes for forward and return data over both the Moon-to-Earth and Earth-to-Moon links may have to be assessed in the context of the overall cross support framework encompassing participating IOAG network assets. For crew safety purpose, we may want to ensure these links in time of spacecraft emergency are supportable by as many network assets as possible, hence the need for a common coding scheme. That means we need to understand whether the LDPC coding capability will be available at these network assets. Otherwise, we have to keep BCH code (for Earth-to-Gateway) and Reed-Solomon convolutional concatenated code (for Gateway-to-Earth) as an option.

Issue 5. Cross link between relay orbiters:

The major unknowns are – (a) What are the relay orbiters to be involved in any cross link communications? We assume eventually there will be some Mars orbiters with relay capability using Lunar Gateway as a staging point for crew transportation. (b) Will there be any non-NASA relay orbiters requiring cross link communications? (c) Will they all be equipped with optical communications capability? Given the above uncertainties, we have to keep two options for Lunar cross links:

a. RF high-rate link: 22 GHz and 26 GHz Ka-bands.
b. Optical link: Our preferred solution.

Issue 6. Proximity links – RF low rate:

It is assumed that there will be relay orbiters during this era providing support to multiple user vehicles. It is further assumed that at least one of them, i.e., the Lunar Gateway, will provide links accommodating simultaneous, multiple access. The major unknowns are – (1) How many user vehicles will there be? (2) What are the signal formats used by these user vehicles? Two multiple access schemes are open to trade-off analysis taking into account spectrum efficiency, power efficiency, resilience to interference, resilience to signal dynamics, and cost ramifications to both relay and user vehicles:

a. FDMA
b. CDMA

Due to the need to combine low rate and PNT, the 2 best SFCG frequency communication & navigation bands are 2025-2110 MHz and 2483.5-2500 MHz. These bands are complementary in mitigating interferences and compatible with regulations and related REC 479-5. PNT can be advantageously completed by the use of the signals transmitted in L-band from the terrestrial GNSS constellations, which are not affecting the SZM.

Note: L-band links for PNT are not recommended as they are not compatible with regulations protecting the SZM.

Issue 7. Proximity links – high rate:

Given the unknowns mentioned above, two options are open to selection –

a. RF high-rate link: 22 GHz and 26 GHz Ka-bands.
b. Optical link.

Similar to the considerations identified for Issue 6, multiple access over Ka-band high-rate proximity link may be achievable via phased array antenna, i.e., multi-beaming implementation, and FDMA with onboard beamforming at the relay orbiter.

Issue 8. Optical communications:

Three standards being developed for optical communications were considered: High Data Rate (HDR), High Photon Efficiency (HPE), and Optical On-Off Keying (O3K). Our initial conclusion is the HPE for all optical links primary for avoiding any extra implementation cost due to multiple approaches. The solution based on the HPE standard meets the data rate requirements for all lunar links, i.e., the proximity links, cross links, and Earth-Moon links. Nevertheless, for the record it has been pointed out by some that:

a. The HDR solution based on the ESA/DLR orange book standard offers the advantage of using in-flight, proven technology. The HDR solution based on the NASA/JAXA/CNES orange book standard could also be used, but this, however, is not yet proven.

b. The future O3K blue book standard could be used too. The advantage is the low complexity in implementation and low implementation cost.

Issue 9. Multiple access over proximity links - CDMA

Regarding multiple access over proximity links, for the CDMA scheme the ability to select from two sets of PN patterns, i.e., the Space Network (SN) SNIP patterns and the CCSDS 415 patterns, is required. The two sets are compatible but different. As of 2018, the SN, which was intended for Earth missions support, only uses the SNIP set of PN patterns, but not the entire CCSDS recommended PN patterns. The larger CCSDS set of PN patterns was created due to the limited size of the original set of SNIP PN patterns that are mostly in use and unavailable for future missions. We suggest both sets of PN patterns be implemented by the Lunar Gateway for another reason, that is, meeting the requirement for the Lunar Gateway to support the Artemis -2, which is SNIP compliant, as a visiting vehicle.

Note: Visiting vehicle, in this context, refers to those non-Lunar Gateway vehicles that will arrive at (via docking operation) and depart from (via undock) the Lunar Gateway. An examples of such vehicles, known as this time, is Artemis -2 Orion.

Issue 10. Forward error correction (FEC) code for Earth-to-Moon link:

It has been asserted by some that all FEC codes, including the high-performance code like LDPC codes, defined in the CCSDS TM Synchronization and Channel Coding blue book are only applicable to spacecraft-to-Earth links. By that assertion, the CCSDS LDPC codes (all coding rates) could not be used for encoding the AOS frames over Earth-to-Moon link, crosslink, or proximity link. CCSDS is however discussing which subset of TM codes will be allowed to uplink. In view of the symmetric property of the AOS space data link protocol, since the CCSDS LDPC codes can be applied to the AOS frames over spacecraft-to-Earth link, we recommend to use them for the AOS frames over Earth-to-Moon link, crosslink, and proximity link.

Issue 11. GMSK modulation for Earth-to-Moon link:

New to the CCSDS Radio Frequency and Modulation blue book is the GMSK modulation for simultaneous telemetry and PN ranging. For the same rationale expressed in (10) above, we decided to apply the same GMSK method for simultaneous data and PN ranging transmitted over the Earth-to-Moon link.

Issue 12. AOS and USLP as space data link protocols for Lunar proximity links and crosslink:

The rationale of departing from the Proximity-1 protocol is as follows -

a. The Proximity-1 space data link protocol as it is in the blue book now will require some modifications suitable for the high-rate proximity links (including Moon-to-Lunar surface and Lunar surface-to-Moon). The UHF-based approach severely limits the link performance. The link protocol, while works very well for Mars relay environment, has a constraint imposed by the field for frame sequence number (being limited to only one octet unlike 3 octets in AOS).

b. The AOS and USLP protocols are symmetric in nature. It has the right property needed for all types of Lunar proximity links and crosslinks.

c. Unlike the TM and TC protocols, the AOS and USLP were designed for high-rate links. It can be readily adopted for purpose of Lunar proximity link and crosslinks, regardless of RF or optical.

d. For supporting multiple user vehicles concurrently, the USLP will preserve and leverage the hailing capability and control mechanism of the Proximity-1 protocol suite.

Issue 13. An overall caveat about the down-selected frequency bands:

Table 4 refers to the down-selected frequencies from the bands defined in the SFCG recommendation. It is noted that other frequency bands, allowed by SFCG, could be employed by agencies when high level networking and interfacing with Lunar Gateway are not required by these missions.

<u>Issue 14. Potential congestion of the 2025-2110 MHz and 2483.5-2500 MHz allocations</u>

There is a possible congestion of the 2025-2110 MHz and 2483.5-2500 MHz bands since it is allocated by SFCG for both the-Earth to Moon and Orbiter to Surface links

The use of these bands could increase significantly if the following is realized:

- a permanent PNT wide band channel is added (about 10% of the band lost)
- a phase out of UHF is planned to preserve Radio Astronomy in the SZM
- the SFCG allocation prepared by several agencies for Orbit to Orbit links is confirmed

Potential mission of this allocation need to take note that in the near future coordination will be required between users.

4. A Conceptual Architecture for Lunar Communications

4.1. Overview of the Lunar Communications Architecture

Given the physical and data link layer characteristics described in the previous section, we propose the future Lunar communications architecture, in conceptual view, as depicted in Figure 1. In addition to the capabilities at lower layers, the architecture features the network layer (or space internetworking layer) functionality enabled by the DTN protocol suite[27,28]. This architecture has the following key characteristics:

- The existence of Lunar space internet: Architecturally similar to the terrestrial internet, the Lunar space internet embodies three types of networks, i.e., the Lunar relay network, the Lunar surface network, the Earth network.
- The existence of Lunar relay network: In this decade, there will be Lunar relay orbiters each of which provides communications with its user space vehicles, in orbit or on surface, over the proximity link. When such relay interfaces involve network layer functionality as depicted in Figure 2, we consider the existence of a relay network.
- The existence of Lunar surface network: In this decade, the deployment of human habitat, multiple landers and rovers, all clustered in South Pole, for conducting exploration activities, will lead to the establishment of Lunar surface network. This type of network will facilitate vicinity wireless communications between the various landed elements including astronaut’s hand-held/body-mounted devices.
- The existence of DTN nodes throughout the end-to-end data path: Each relay orbiter, its user vehicles, the relevant Earth stations, and the various Mission Operations Centers (MOCs) will all serve as DTN nodes to achieve reliable, robust, efficient end-to-end communications path.

- The existence of high-speed trunk link: As in the case of Lunar Gateway, its trunk links with Earth network will include 26 GHz/22 GHz Ka-bands and optical capabilities to support a variety of user missions.

Figure 1. Future Lunar Communications Architecture (Up To ~2021) – A Conceptual View

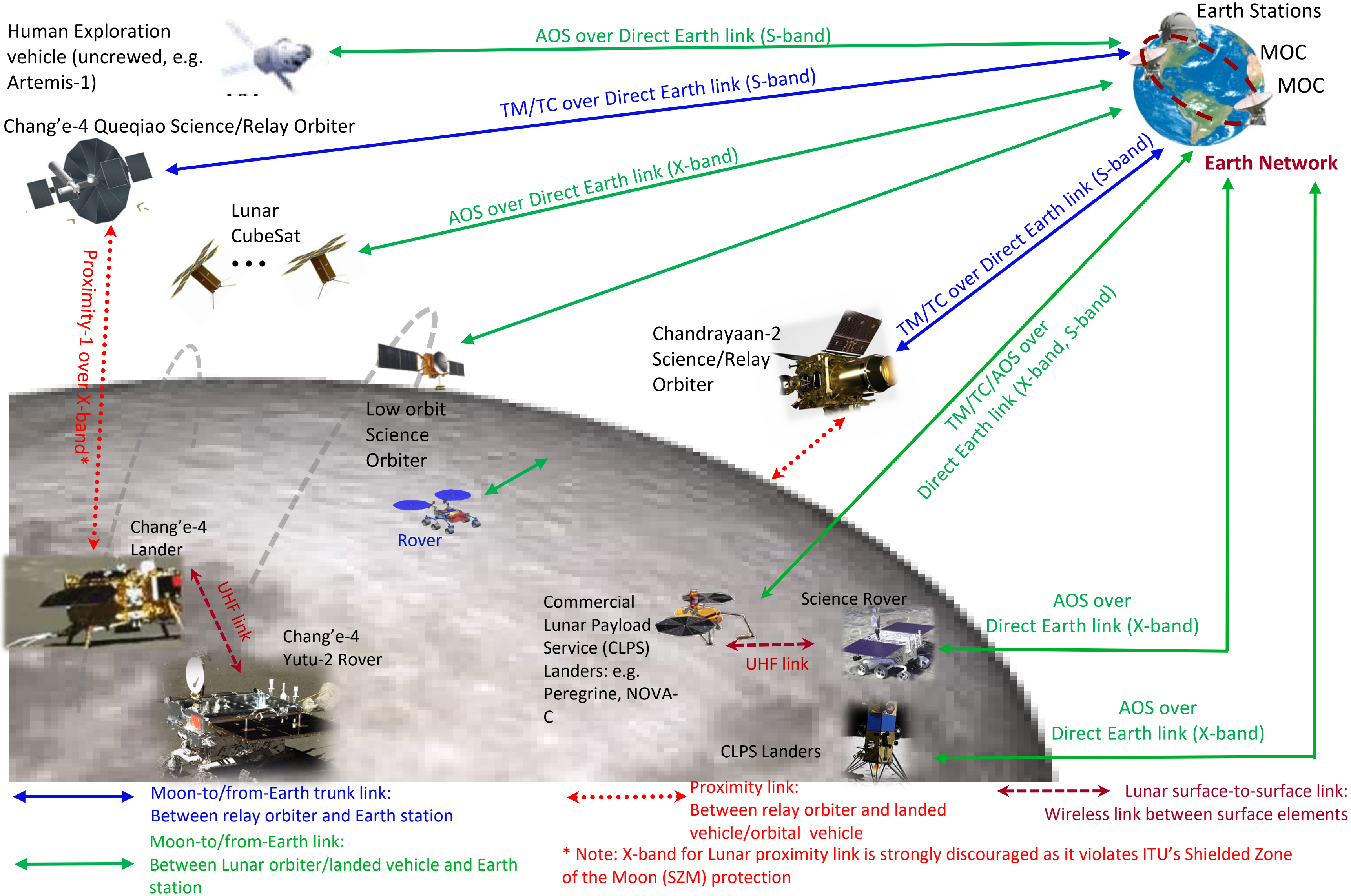


Figure 2 Future Lunar Communications Architecture (Up To ~2025) – A Conceptual View

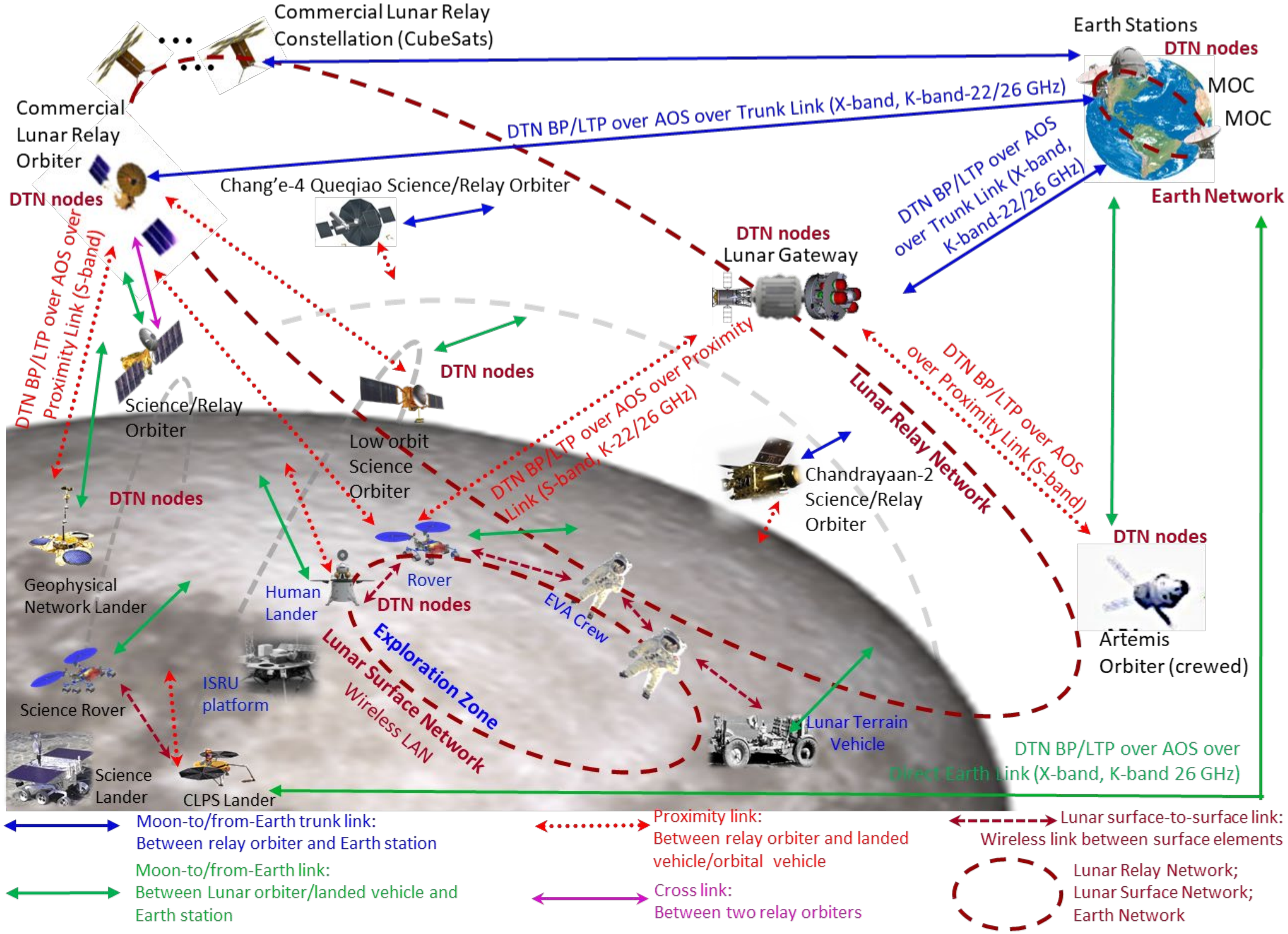
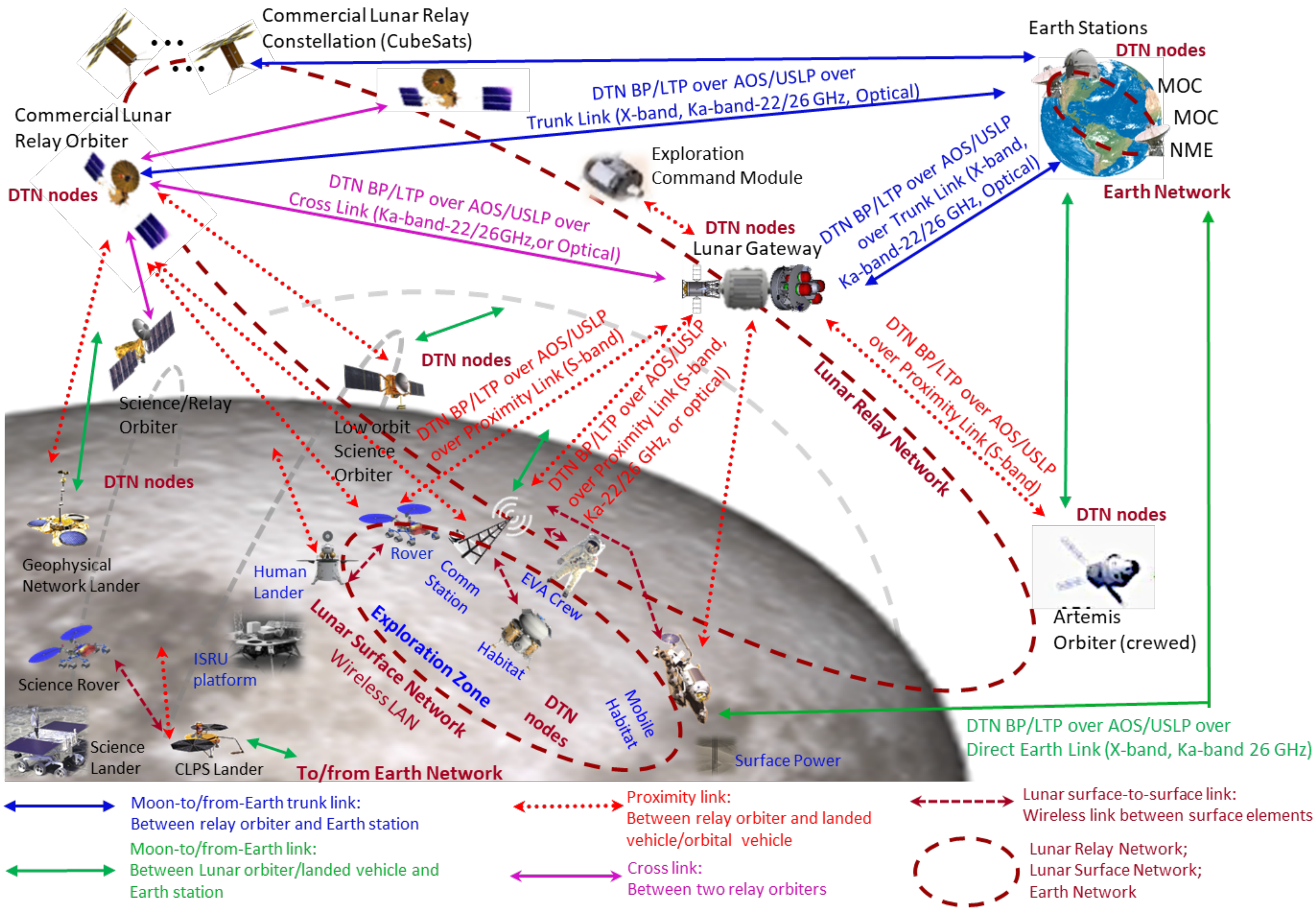


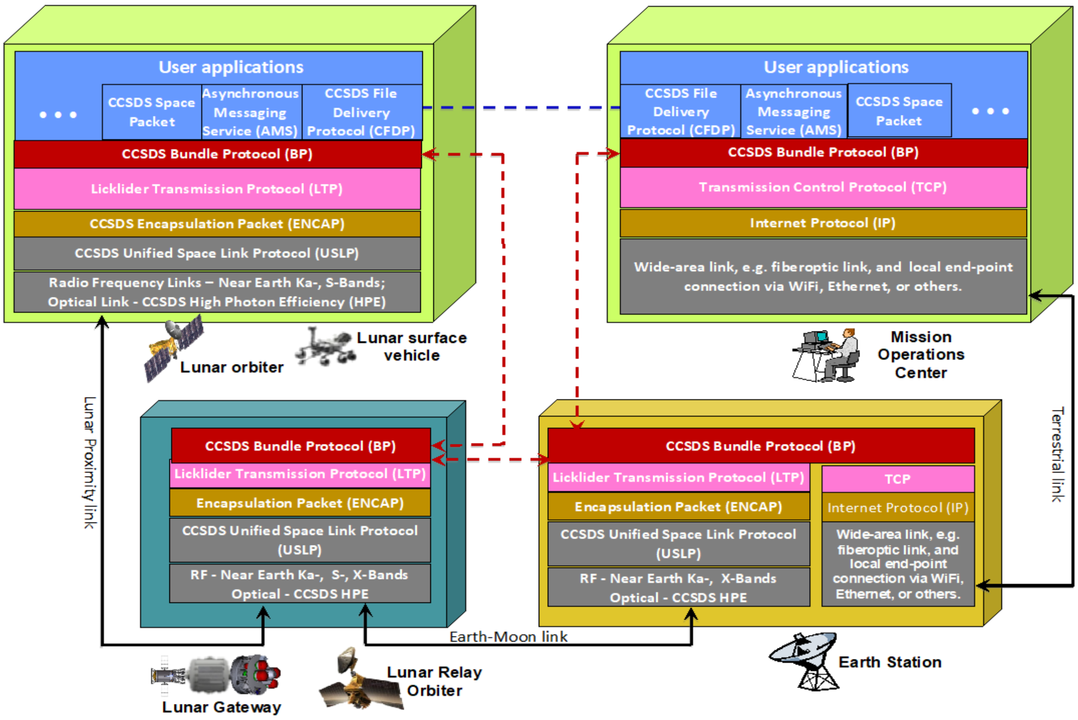
Figure 3 Future Lunar Communications Architecture (Up To ~2030) – A Conceptual View



4.2. Lunar Space Internet – Protocols and Use Cases

The protocol stacks for the Lunar space internet with respect to four different use cases have been constructed -

Use Case 1: For all future Lunar missions including high-rate missions, the end-to-end communications feature the DTN Bundle Protocol (BP)[27] for end-to-end data transfer and routing, the Unified Space Link Protocol (USLP)[7] for all space links, and the provision of relay services -

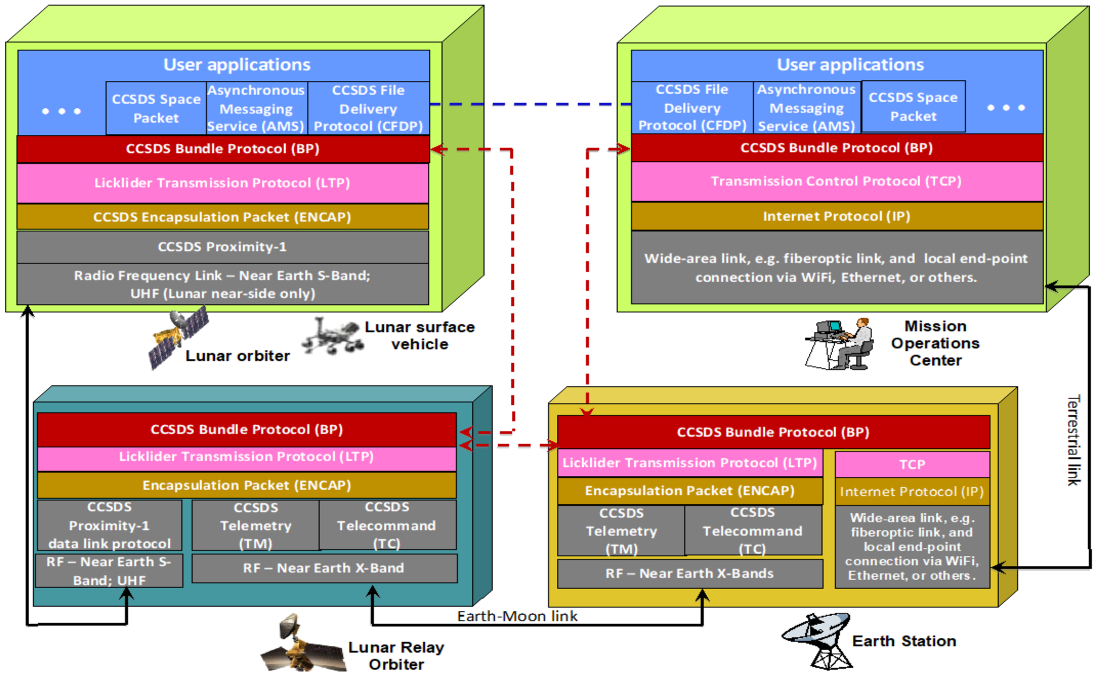


a

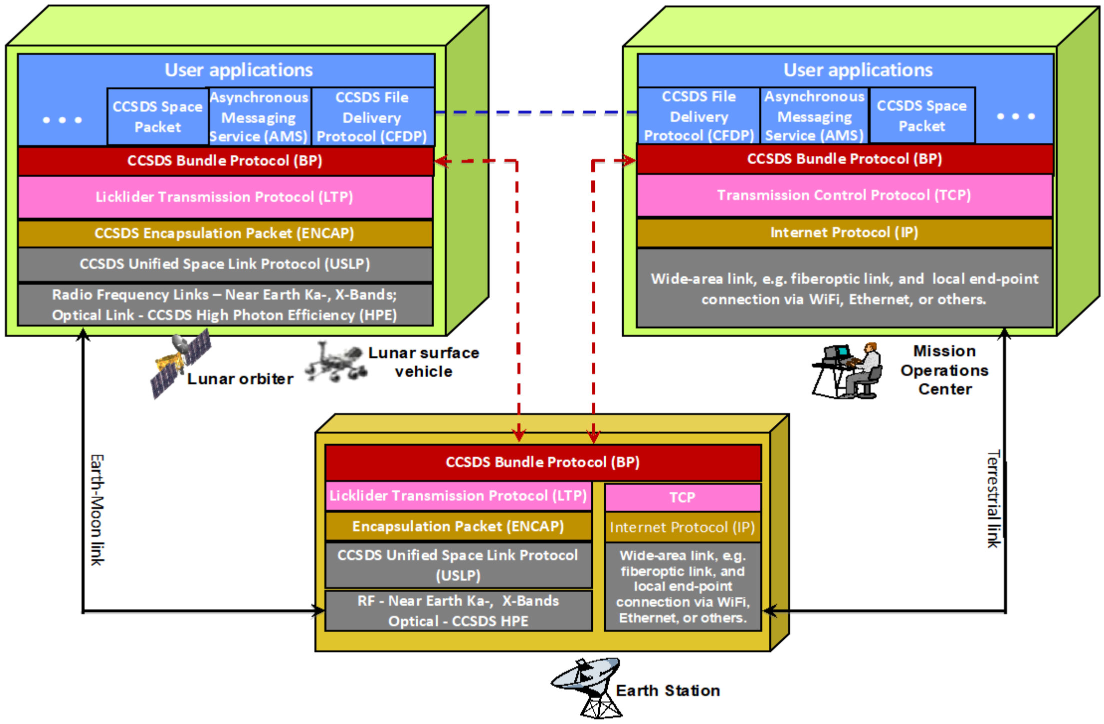
Use Case 2: Similar to Use Case 1, this is only specifically for some low-rate missions that prefer to make use of the current space link protocols –

A couple of points must be noted here:

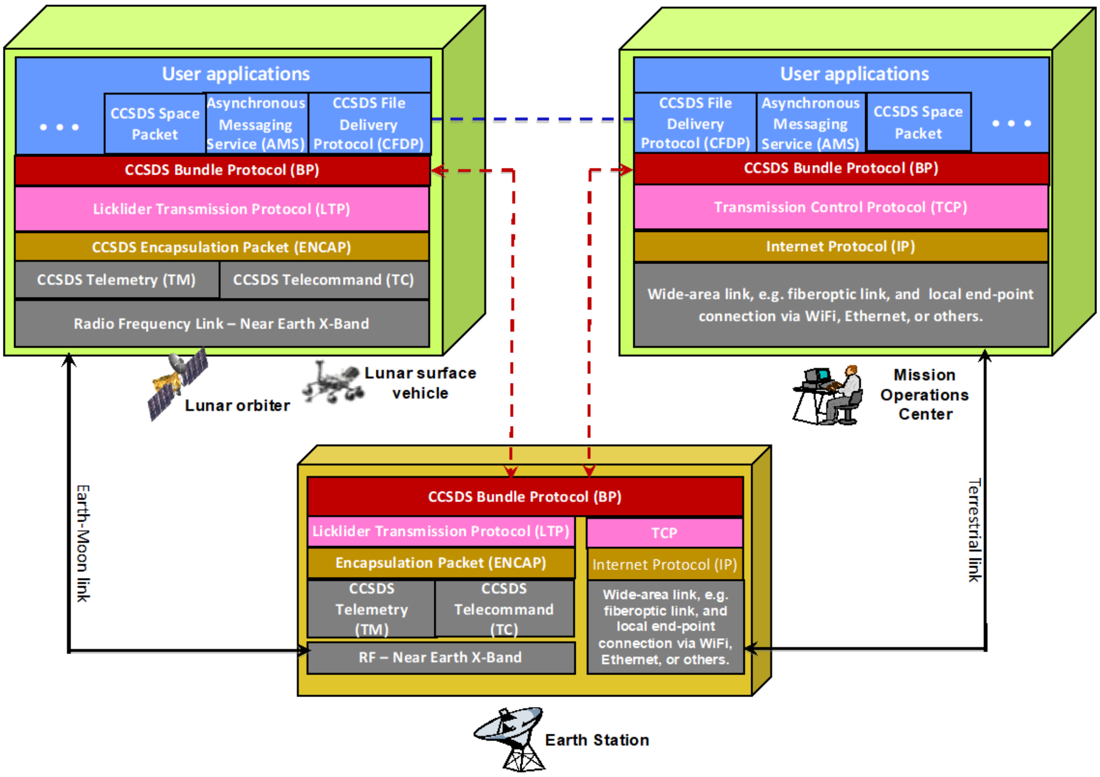
- The UHF-band for proximity link is shown in the protocol stack along with S-band. The use of UHF, however, is forbidden for situations where proximity link communications take place in Shielded Zone of the Moon (SZM) as defined in ITU-R[42]. For surface vehicles, for instance, located at SZM, any UHF communications would violate the regulation for radio-quiet zone. As a result, there is a potential for this UHF allocation to be phased out in support of the SZM and the use of this band purely for Radio Astronomy.
- Use Case 2 does not apply to Lunar Gateway as it employs only USLP (or AOS) at space data link layer for all links in all directions.



Use Case 3: Similar to Use Case 1, this is for all future Lunar missions including high-rate missions; the only difference being no relay involved in the communications path -



Use Case 4: Similar to Use Case 2, the only difference is there is no relay involved in the communications path -

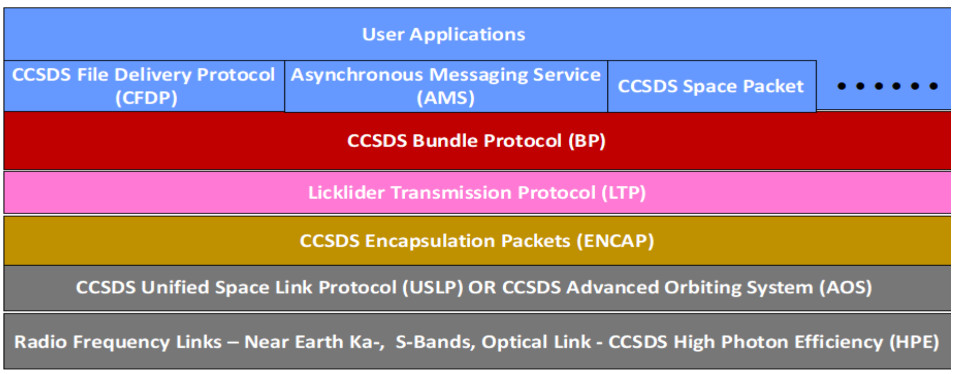


While in the use cases above all DTN stacks include the LTP[28], for missions that can tolerate certain data loss or for missions that use heavy enough coding at the lower layers and can accept unrecoverable data loss on the rare occasions when the coding isn't strong enough, there is no need for LTP. The downside of relying on the BP alone for retransmission is that the mechanism has no negative acknowledgments. The only means that triggers retransmission is the expiration of a timer prior to receipt of a positive acknowledgment.

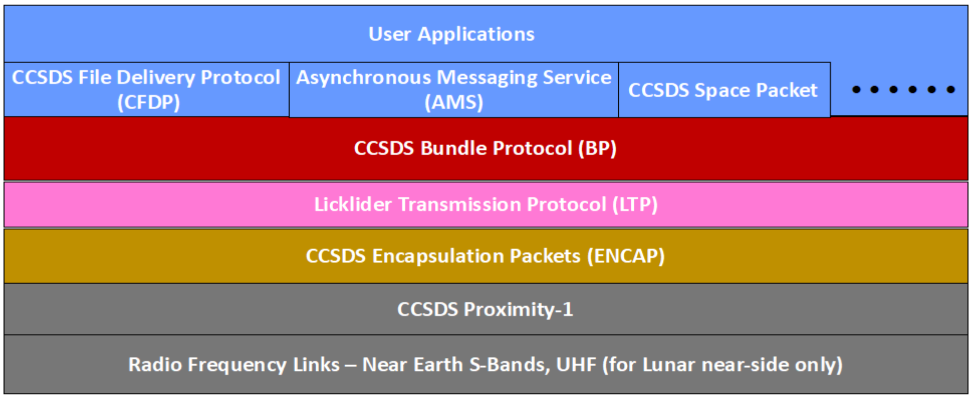
4.3. Lunar Space Intranet - Protocols and Use Cases

Furthermore, for interfaces between the elements within a network, it is necessary to standardize the protocols at all layers.

For the Lunar Relay Network, we propose the intra-network protocol stack as follow -

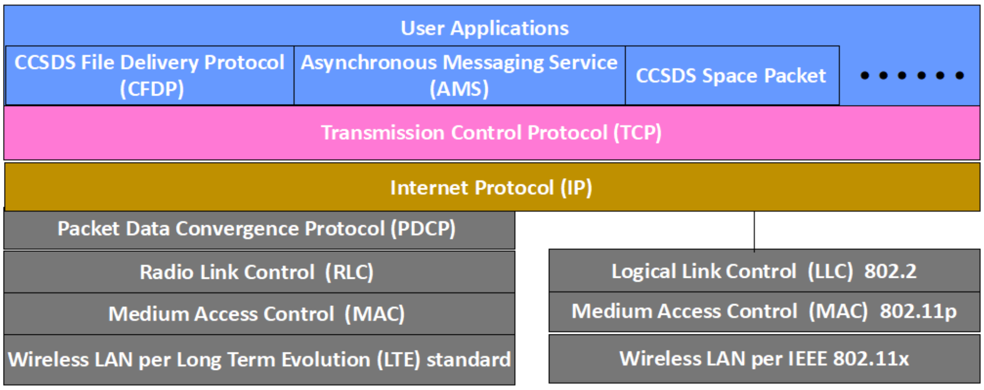


A variation from the above is also proposed to accommodate some low-rate missions that prefer to make use of the current space link protocols -



Note: Proximity-1 for data link layer is only for low-rate Lunar missions that require no interface with LOP-G.

Specific for the Lunar Surface Network, commercial solutions prevalently deployed for terrestrial internet and wireless LAN are encouraged. Nevertheless, to ensure a high degree of interoperability among communication capabilities resident at multiple surface vehicles, the following protocol stack is proposed:



Note: The wireless LAN for each Lunar surface network will be based on either LTE or IEEE 802.11x standard subject to selection by the respective commercial provider.

4.4. Lunar Surface Network

During this decade, it is expected that international Lunar surface campaigns will lead to the deployment of a multitude of surface vehicles (e.g., landers and rovers) and facilities for exploration and science (e.g., telescopes and instruments) in the various regions of the South Pole. More persistent surface-to-surface communications infrastructure will be built to support the various sample return missions, the series of commercial small lander missions, and the crewed surface exploration including its robotic precursor missions. The following is a list of potential surface elements:

- Geophysical observatory
- Small science landers
- Robotic survey rover
- Radio telescope
- Surface communications station
- Crewed rover
- Moon base station
- Communications with astronauts on the surface during EVA
- Solar physics telescope
- Medium-sized science landers
- Robotic exploration rover
- Landing beacon
- Communications tower
- Crewed landers (descent & ascent modules)
- Cargo landers or other unmanned elements (ascent & descent modules)

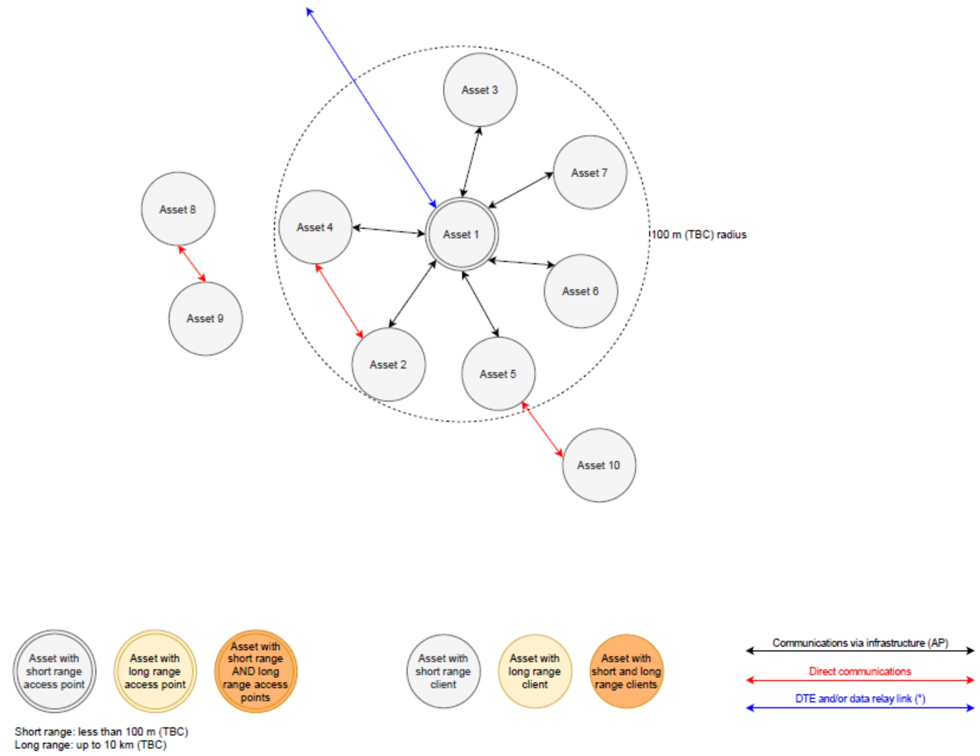
Scenarios

The main use for a Lunar surface network will be supporting communications in a relatively small area for a mission involving multiple assets, with the exploitation of data relay to the Lunar Gateway, to satellites in lunar orbit or direct to Earth links.

The Lunar surface communications network can be mapped into scenarios that evolve over time, where initially a single communication cluster is deployed in an area without any pre-existing network. In this initial scenario, within the cluster, multiple assets are co-located. As the number of missions grow, multiple clusters are deployed and the area covered can be extended. The new clusters can be connected to each other, and the lunar surface network grows into an architecture like the one shown in the following figures.

In particular, an initial single cluster architecture could cover a short range (up to ~100 m TBC, exemplified in Figure 4), or a long range (up to ~10 km TBC, Figure 5).

Figure 4. Single cluster lunar surface architecture, short range(*)



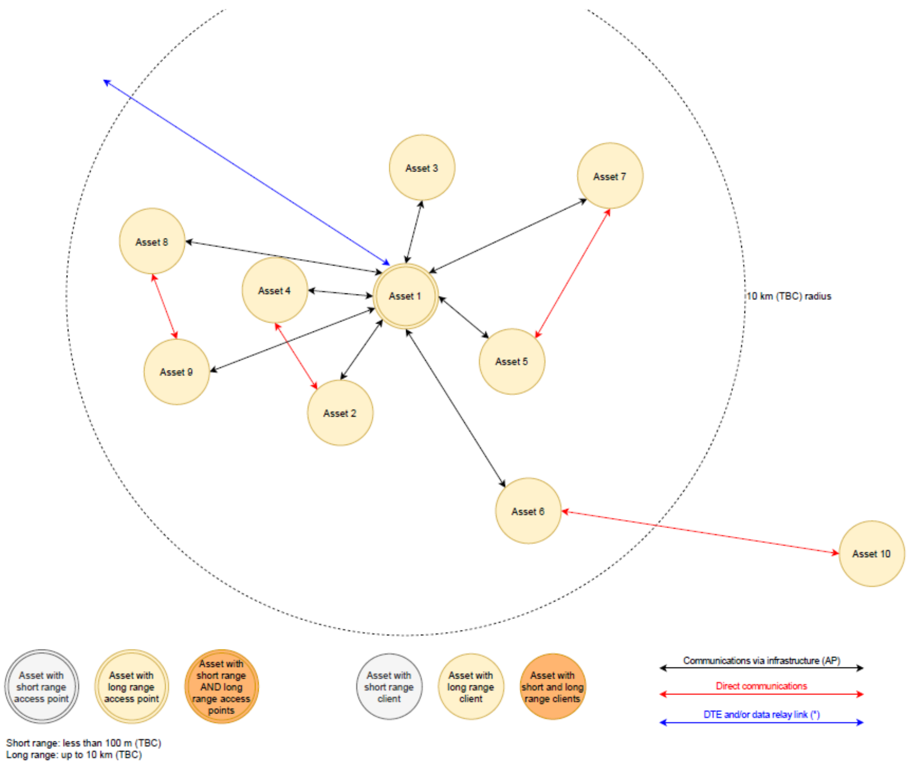
(*) data relay link note: at least one asset is supposed to be equipped with additional DTE and/or data relay link. An example is provided in the diagram. All the other assets may or may not have an additional DTE or data relay link, depending on the specific mission needs. These are not shown in the diagram.

In the identified scheme, two types of assets are identified:

- Assets equipped with Access Point (AP). The communication equipment of these assets acts like a communication hub.
- Client assets. These can either connect to the AP to enable communications or can communicate directly among each other.

In the above figure, an abstraction is made about the nature of the assets. In fact, the same kind of asset (e.g. a rover) might be either employed as a client or could be used as an AP, depending on the mission needs. The data between client assets could nominally be routed through the AP asset, that acts as a communication hub and serves multiple clients.
A special mention is needed for the direct communications between client assets, that do not need to be routed via the AP. This requires a special treatment also from technology point of view. To support this direct communications it is assumed that either the client assets establish an additional dedicated link, in addition to the AP link, or that the AP link is disconnected and reconfigured to allow the direct communication. In the latter case, the client asset can act as an AP with reduced capabilities and can be able to connect to a reduced number of clients. It is clear that the direct communications between asset is limited in distance to the range of the communication equipment employed.

Figure 5. Single cluster lunar surface architecture, long range (*)



(*) data relay link note: see Figure 4

If a reduced number of assets need to travel over distances larger than ~10 km (TBC) from the AP, they would likely not rely on a surface network infrastructure. Instead, they would use a DTE/orbiter relay link. Furthermore, when extending the range of coverage over the kilometer range, terrain aspects can play an important role and further constrain the use of the surface network; also in this case a DTE/orbiter relay link might be the choice to cover the communication needs.

Another possibility worth mentioning is a single cluster that embeds both short range and long range capabilities, to increase the communication coverage support.

When multiple clusters like the one shown in the previous figures are deployed over time, they would lead a multiple cluster architecture. A concept of this architecture is shown in the following Figure 6, where three clusters are included.

Figure 6. Multiple clusters lunar surface architecture. (*)

(*) data relay link note: see Figure 4

Technology aspects

The scenarios identified above have to be supported by adequate technology.

For short range, i.e. to cover distances in the order of 100 m (TBC) the following can be envisaged:

- Communications via AP with a significant number of assets (larger than 2 to 3):
  - WiFi seem the most promising solution given the large heritage from terrestrial applications. 3GPP solutions are also suitable also for short range; however, given the higher complexity of the 3GPP infrastructure, in general it is preferable the simpler WiFi solution, unless the mission identifies different drivers for the choice (considering hardware availability, Quality of Service, etc).

- Direct communications between clients:
    - With a reduced number of clients (2 to 3, TBC), it is possible to retain the WiFi technology, thanks to the “soft access point” feature. When activated, one asset becomes an AP itself with reduced functionalities. In this case, the nominal link via AP, if present, might need to be dropped to establish the “soft access point”. WiFi allows to maintain high data rate transfers. Note that the distance covered might be reduced to some 10s of meters.
    - Ultra-Wideband technology (UWB) is under development for terrestrial applications. In addition to data communications, UWB tags can provide positioning capability for assets in reference to some pre-deployed UWB anchors with known positions. A deeper investigation about this technology for the lunar surface communication is advised to better understand data rates, coverage and frequency allocation limitations. At present, in Europe the TRL of UWB solution for space applications is between 3 and 4 and developments are ongoing to increase the TRL level, as well as characterizations of COTS equipment.
    - In case of simple network structure (2 to 3 clients, TBC) and with low to medium-high data rate needs, it is possible to employ dedicated inter-assets links. Heritage with such kind of equipment can be for example a UHF communication suite for astronauts’ EVA, however taking into account that UHF is not allowed in the SZM[42].

For Long range communications to cover distances in the order of 10 km (TBC) the following can be envisaged

- Communications via AP. With a significant number of assets (larger than 2 to 3):
    - 3GPP (LTE, 5G)[43,44] seem the most promising solution given the large heritage from terrestrial applications and its purpose to cover larger areas. The suitability of the SFCG frequency allocations set for 3GPP (LTE, 5G) technology should be assessed, or alternatively an extension of such set could be proposed if required.
- Direct communications between clients:
    - Even if 3GPP does generally allow the special case of direct client-to-client communications, this has not yet been implemented in terrestrial applications. Note that the distance covered might be reduced when employing this method. Further analysis is needed to determine if 3GPP is the viable solution also for asset-to-asset communications at long range.
    - In case of simpler network structure (2 to 3 clients, TBC), it is possible to employ dedicated inter-assets link. Heritage with such kind of equipment can be for example from UHF or S-band inter-satellite links, however by frequency plan adaptation in order to adhere to current SFCG allocations[1]. This kind of link can be similar to the one used for mothercraft-to-daughtercrafts communications (used for example in Rosetta, Proba-3, Hayabusa-2, MMX, etc.). UHF is not suitable when the data rate is higher than 1 Mbps (TBC) and for use in the SZM[42], in this case S-band links can be considered (up to 30 Mbps TBC). To further increase the data rate above 30 Mbps, evolutions of the inter-satellite equipment in K-band can be considered.
- Infrastructure communications: this link is the used in 3GPP to make the AP assets communicate to each other with specific protocols - to allow for example the hand-over from one AP to the other of a moving client. This is standardized by 3GPP as the "X2

interface". As an alternative, a link between AP assets can be realized using dedicated inter-asset link as described in the previous bullet.

The above considerations are summarised in the following Table 5. technologies for Lunar Surface Communications Table 5, detailed frequency band allocations are reported in Table 4.

<table>
<tr><th>Coverage</th><th>Type of link</th><th>Data rate</th><th>Technology</th></tr>
<tr><td rowspan="7">Short range (100 meters)</td><td rowspan="4">Communications via AP (clients via AP)</td><td>Low: < 1 Mbps</td><td rowspan="4">802.11 WiFi, CCSDS 883.0-B-1 [41] or 3GPP on a mission-need basis</td></tr>
<tr><td>Medium: 1-5 Mbps</td></tr>
<tr><td>Medium-high: 5 Mbps – 50 Mbps</td></tr>
<tr><td>High: 50 Mbps – 1 Gbps</td></tr>
<tr><td rowspan="3">Direct communications (client to client)</td><td>Low: < 1 Mbps</td><td rowspan="2">802.11 WiFi, CCSDS 883.0-B-1 [41] or 3GPP on a mission-need basis or dedicated inter-assets links in UHF, like astronaut's EVA communications equipment (UHF not allowed in the SZM[42])</td></tr>
<tr><td>Medium: 1-5 Mbps
Medium-high: 5 Mbps – 50 Mbps</td></tr>
<tr><td>High: 50 Mbps – 1 Gbps</td><td>802.11 WiFi, CCSDS 883.0-B-1 [41] or 3GPP on a mission-need basis</td></tr>
<tr><td rowspan="6">Long range</td><td rowspan="4">Comms via AP (clients via AP)</td><td>Low: < 1 Mbps</td><td>3GPP:
LTE up to ~2 km,
5G beyond 1 km
(note 1)</td></tr>
<tr><td>Medium: 1-5 Mbps</td><td>3GPP:
LTE up to ~500 m
5G up to ~10 km</td></tr>
<tr><td>Medium-high: 5 Mbps – 50 Mbps</td><td>3GPP:
5G up to ~1km</td></tr>
<tr><td>High: 50 Mbps – 1 Gbps</td><td>3GPP:
5G up to ~500m</td></tr>
<tr><td rowspan="2">Direct communications (client to client)</td><td>Low: < 1 Mbps</td><td>Dedicated inter-assets links in UHF or S band (UHF not allowed in the SZM[42])</td></tr>
<tr><td>Medium: 1-5 Mbps</td><td>Dedicated inter-assets links in S band</td></tr>
</table>

		Medium-high: 5 Mbps – 50 Mbps	Dedicated inter-assets link in S-band (up to 30 Mbps) or K-band
		High: 50 Mbps – 1 Gbps	Dedicated inter-assets link in K-band
	Infrastructure communications	High: 50 Mbps – 1 Gbps (TBC)	3GPP link between AP stations or dedicated high rate inter-asset link

Table 5. technologies for Lunar Surface Communications

(note 1): the indicated ranges are for 1 Mbps rate. For lower data rates, higher ranges can be achieved in line-of-sight conditions (for example, 0.1 Mbps with LTE and 1 Mbps with 5G at ~20 km).
Note: 1.8 GHz 4G LTE lunar wireless shall be avoided in the SZM, and therefore any operational use of 1.8 GHz 4G LTE, to avoid real issues with SZM Radio Astronomy in the mid-term and long terms

4.5. Security Architecture for Lunar Communications

Security mechanisms are viewed as an inherent element of the Lunar communications architecture. While not explicitly shown in the protocol stack diagrams in the above sections, authentication or encryption must be applied at one of the following two layers:

- Network Layer security – applied either within the DTN stack using Bundle Security Protocol (BSP)[29]/Streamlined Bundle Security Protocol (SBSP)[30,31] or within an IP stack using Internet Protocol Security (IPsec).
- Space Data Link Layer security - applied to the data link contents using Space Data Link Security (SDLS) protocol[32,31]. The SDLS defines a security header and trailer for applying authentication and encryption. The frame headers are protected, but left in the clear.

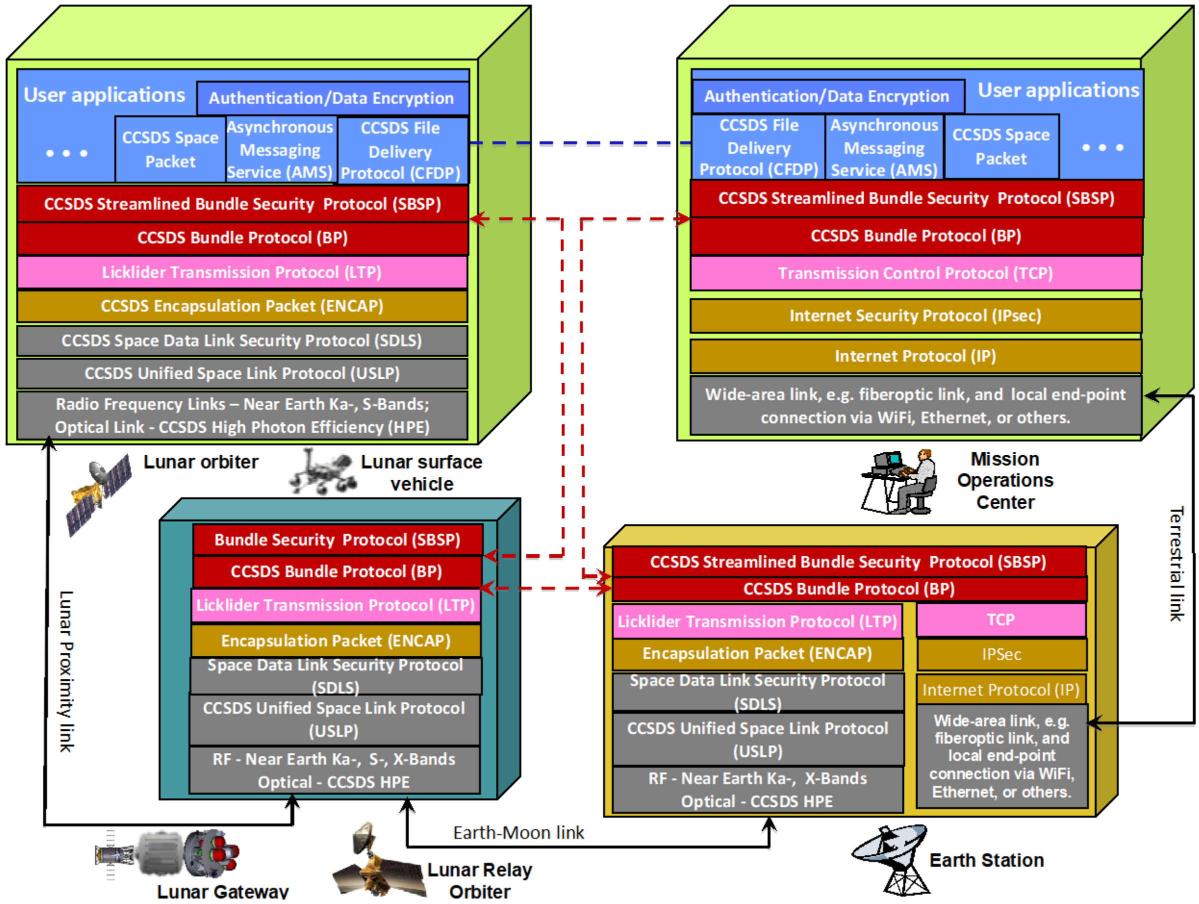
Application Layer security may be applied to the data by the user application for providing security services in addition to any such services provided at network layer or space data link layer.

We recommend the following general security policy be adopted by the IOAG member agencies:

- All Lunar missions, regardless of robotic science, or human crewed missions, should use the SBSP or SDLS using AES-GCM in authentication mode, at a minimum, for all links in all directions.
- All crewed or human exploration missions should use the AES-GCM in Encryption, or Authenticated Encryption mode with 128-bit (or larger) keys, for all links in all directions.
- All robotic science missions should use the AES-GCM in Encryption, or Authenticated Encryption mode with 128-bit keys, for all links in forward direction.

- Adopt an agreed approach for key management. This is because, while there exists a relevant CCSDS book for operational concept and rationales, the SDLS Protocol – Extended Procedures[33] that specifies the CCSDS standard practices for key management are yet to be published.

To illustrate the security approaches in the overall Lunar communications architecture, the protocol stacks, as integrated with security mechanisms/protocols, for Use Case 1 are shown below:



Again, it is important to note that not all three layers (application, network, and data link layers) of the security mechanisms/protocol have to be implemented for a given mission or mission set. The protocol stack diagram shows them all merely for the purpose of depicting a viable, inclusive security architecture.

4.6. Cross Support Services at Space Data Link Layer

A key ingredient of the future Lunar communications architecture described in Sections 4.1 – 4.3 is the space internetworking capability enabled by the DTN protocol suite. The cross support to Lunar missions by the Earth communication assets, owned by the IOAG member agencies and commercial service providers, will be through the Bundle Protocol with the transfer of DTN bundles between each user's Mission Operations Center (MOC) and the service providing asset, e.g., a ground station. One may rush to conclude that the current cross support transfer services, based on the CCSDS Space Link Extension (SLE)[34,35,36]/Cross Support Transfer Services (CSTS) standards[37,38,39] and used by almost all agencies, will become irrelevant and obsolete. However, our past experience in operating the spacecraft has shown that monitoring and controlling a spacecraft through the rudimentary level of the communication system is essential from time to time. That means a cross-supported mission must be able to conduct the following scenarios by directly “poking” into the space data link layer without or bypassing the DTN layers:

(1) Link performance analysis, anomaly detection and isolation, troubleshooting
(2) Special configuration and control: bootstrapping flight computer and hardware commanding
(3) Spacecraft emergency and contingency modes
(4) Certain mission critical events
(5) Space vehicles and ground systems that lack DTN functionality

Therefore, out of necessity the provision of cross support services at the space data link layer by the Earth communication assets will persist into the DTN era.

4.7. Impact of commercial services

Since the 1990s there has been a very health and active market for private investment within the area of satellite communications. These companies, offering TV and internet via satellite, number over 20 and is truly global. In the late 2010s there has been a move towards LEO constellations offering internet services. All of which show a real appetite to offer commercial services to customers.

During the 2010s there has also been a rapid increase of private investment within space missions, outside communications, with over $8.9 million had been invested in 2020[45] alone. Each of these areas offering services, to an established customer base, previous only offered by space agencies.

It is clear that the private investment is available for missions that have a clear customer base. It for this reason that NASA’s Commercial Crew and Cargo initiative, started in 2011, has been very successful. With NASA being the anchor customer, you can give certainty to the markets that if successful a return on investment. Clearly, this approach has been shown to work as there are now frequent commercial re-supply missions and we are starting to see regular commercial crews to the ISS as well.

There is also commercial offering of TT&C services to space agencies and companies for LEO and GEO services by several companies. These usually use relatively small antennas (5m - 15m) to deliver these services. The realms of deep space offering (with antennas greater than 20m) is still limited to space agencies, with very few offering from commercial companies or academia. This is due to the cost of these antennas, as well as the market access which are limited to missions from space agencies.

For the Moon, which sits between near and deep space, the use of 15m antennas is too small and the use of <25m is an over kill. Therefore, the sweet spot for the size of antenna is in the region of 18m. Which unfortunately is an antenna diameter that is not regularly available and would require development. This is one of the barriers for the that deployment of a “lunar ground infrastructure” in the support of cis-lunar missions. Another factor is the limited number of missions that are currently flying around cis-lunar, with the first few future missions being landers with limited lifetimes (usually one lunar day). Therefore, if you were to invest in this network, then you would need to ensure that the 18m antennas could be used for other missions. This in itself is an issue as 18m antennas are not big enough for deep space and too large for LEO, so limiting their utilization to a very niche number of high-altitude Earth orbiting space agency missions.

It is therefore essential for successful commercial lunar communications to have an anchor customer. The purpose of which is to overcome the fragile nature of the lunar missions to give a level of certainty to the market to initiate the investment. A similar initiative to NASA’s Commercial Crew and Cargo needs to be put in place for the Moon, that addresses these points. Otherwise, the concept of the lunar economy is still too uncertain and risky for private investors and it will stay in the domain of the space agencies.

This has started to happen with the development of ESA’s Moonlight program and the NASA Commercial Lunar Payload Services (CLPS) and Human Landing System (HLS). By clearly indicating that a space agency can act as an anchor customer for the delivery of communications, navigation and transport services. Clearly the transport elements rely heavily on the communications and navigation. To further accelerate the development of these two, the CLPS providers have been instructed, by NASA, to find alternatives to agency assets. i.e., not to rely on DSN for the communication and navigation. This is both useful for the direct to Earth services and the relay offering.

The result of which is that several companies have started offering commercial services to the CLPS missions starting in 2022. These providers have created global networks of private, academic and research organizations to use alongside the agency assets. The ultimate aim would then be wholly reliant on only commercial services once a permanent robotic presence is established on the Moon. The success of these missions will create belief in the market to ensure that more private assets will become available to support future missions. Conversely, failure will dent confidence and make it harder to gain private investment.

As the CLPS providers are using different types of antennas (space agencies, academia and private), the need to adopt standards is key. The space segment needs to be able to talk to the space agency assets and so they adopt CCSDS standards. As a result, the academia and private stations adopt CCSDS to be compatible with the spacecraft and therefore with the agency’s systems. This also allows these private assets to cross-support agency missions, potentially making them sustainable as more services can be offered to more customers.

In parallel, Artemis is a developing a commercial approach to landing the first woman and the next man on the Moon in mid-2020. This endeavor is international, through the Artemis Accords and the Lunar Gateway. This Human Spaceflight program has the potential to generate a large amount of data both towards the Moon and from it. In doing so has the potential in accelerating the need for 18m antennas to support these high data rate communications. As with the robotic missions, the market requires a level of certain in this program before they will be willing to invest in either the space or ground segment.

However, it must be stated that to minimize the risk of local interferences for all users. This must include the number of allocated frequencies intended to be addressed for radioastronomy on the far side of the Moon (SFCG and non SFCG lunar frequencies, as well as ITU and non ITU bands for radioastronomy). It is imperative to promote the use of the SFCG frequency bands by commercial lunar missions (private orbiter, lander, private robotic or crewed outpost, for example), this to also minimize the risk of interferences with terrestrial systems, since all the SFCG lunar frequency have been already intensively checked and validated as not creating interferences for terrestrial systems, and this will be also the case for potential new non space research SFCG lunar frequencies.

The 2022-2024 timeframe will define the success of private lunar communications and will be dependent on the success of the commercial robotic missions as well as a more concrete timetable for human lunar missions. Both activities will drive the confidence of the market and therefore the timescales for the development of both the Earth based and relay commercial lunar communication services.

5. Lunar Relay Services

The relay services are end-to-end services involving:

- Multiple physical links: Proximity link, Direct-To-Earth links, Direct-From-Earth link
- Interfaces at multiple layers: Physical, data link, and network layers

The exhibition of network layer service and multiple links across two planetary bodies, Moon and Earth, points to the need for formalizing Lunar relay services. In this section, we have defined the various types of Lunar services, relay methods, relay access modes, and relay service initiation modes.

5.1. Relay Service Types

The primary service provided by relay vehicles is the relay data service. It is an end-to-end service that offers the transfer of a single interoperable entity over one or more assets, i.e., relay assets, between the two end points. This single interoperable entity must be at, or at a higher level than Layer 3 on the ISO model. This single interoperable entity shall be created at the start point and preserved during its transition through the relay asset(s) until acceptance at the end point.

For the lunar communications architecture this data entity is a DTN bundle. As shown in Figure 1, a Lunar relay network is comprised of one or more Lunar relay orbiters and the user vehicles. The end-to-end transfer of relay data across the Lunar relay network and Earth network resembles the function of terrestrial internets. As such, the Lunar relay data service is in fact a Space Internetworking Service.

In addition to the relay data services, the involved relay asset(s) may provide other types of services, e.g., network time service, in-situ tracking service, and in-situ navigation service. Table 6 gives a definition for each of the Lunar relay services.

Table 6 Lunar Relay Services - Types of Services

Service Type	Description
Space Internetworking Service	Provides routed, assured, secure delivery of mission data using DTN protocol suite
Network Time Service	Distributes, synchronizes, and manages time both relative to the central body and with regard to an absolute reference system. Provides network-wide time knowledge using a Network Time Protocol (NTP)
In-situ Tracking Service	**Ranging:** Measures the time delay between the user vehicle and the relay orbiter using RF or optical transmission (convertible to distance)
	Doppler: Measures and time tags the phase of the transmitted forward carrier and/or the received return carrier at the relay orbiter
	Antenna Pointing Angle: Measures the pointing angle of the relay RF antenna or optical terminal as it tracks the user vehicle
In-situ Navigation Service	**Positioning:** Determines the location of the user vehicle, on Lunar surface or in Lunar orbit, based on available tracking data types
Application Layer Services enabled by relay services are:	
End-to-end file service	Transfers files bi-directionally between a user vehicle and ground system or between two user vehicles. The preferred file transfer protocol is the CCSDS File Delivery Protocol (CFDP).
End-to-end messaging service	Transfers messages bi-directionally between a user vehicle and ground system or between two user vehicles. The preferred messaging protocol is the CCSDS Asynchronous Messaging Services (AMS).
End-to-end space packet service	Transfers CCSDS space packets from a user vehicle to ground system or between two user vehicles

5.2. Relay Methods

Relay methods could be bent-pipe and store-and-forward. The store-and-forward method is proposed for Lunar relay network given the assessment summarized in Table 7.

Table 7 Lunar Relay Services – Relay Methods

Relay method	Pros	Cons
Bent-pipe	1. Simplicity in relay mechanism. The relay asset is essentially a physical layer entity, like a piece of wire. 2. Minimum on-board processing is to take place. Latency is low. 3. Minimum demands on additional on-board resources, e.g., memory and data store.	1. Fragility in service provision, as the relay asset must maintain a guaranteed visible, direct path with both source and destination throughout the contact period for data transfer. 2. For Lunar relay, there is no equivalent of geosynchronous or geostationary orbits as a stable orbit for user vehicles' view. 3. Difficulty in providing higher level and value-added services to user vehicles. For example, provision of network layer functionality, e.g. dynamic routing, is not feasible.
Store-and-forward	1. Flexibility in service provision, the relay asset does not have to rely on both source and destination being in view throughout the contact period for data transfer. 2. Amenable to the provision of higher level and value-added services to user vehicles. For example, provision of network layer functionality, e.g. dynamic routing, is feasible.	1. Complexity in relay mechanism. The relay asset must provide physical, data link, and network layer capabilities for interfacing with both its source and destination vehicles. 2. Heavy demands on additional on-board resources, e.g., processing power and data store.

5.3. Relay Access Modes

For user vehicles to access the proximity link, both single access and multiple access modes should be supported by the relay orbiters. For multiple access to proximity forward link, i.e., from a relay orbiter to multiple user vehicles, given the 1-to-N topology, a "simplified" TDMA scheme, i.e., time-sharing at the granularity of Proximity-1 frames or USLP frames, is viable. On the return link, either the FDMA or CDMA approach should suffice. These could be accompanied by a multi-beaming approach using phased array antenna on board the relay orbiter.

5.4. Relay Service Initiation Modes

For user vehicles to initiate the access to proximity link, hence relay services, it is recommended that the future Lunar relay networks departs from the current pre-scheduling approach. The User-vehicle initiated Service (UIS) mode is preferred. Through this mode, the access to relay services would be initiated by user vehicles on demand, thus accommodating both routine and opportunistic service requests in an autonomous fashion. Included in the UIS mechanism are two processes:

- The link acquisition mechanism (or protocol) for access to the proximity link: An example of such mechanisms is the CCSDS Proximity-1 hailing control mechanism.

- The UIS service acquisition protocol for requesting relay services at application layer. The request can be specified as exactly desired or can be specified with open-range parameter of time, duration, data rates, code, etc. The request can be confirmed and accepted for service execution or queued for later execution (in a multi-user environment).

The UIS, therefore, provides some flexibility for user vehicles to get their relay needs fulfilled in multi-user environment where the simultaneous demands exceeds the multiple access capacity of the relay orbiter's proximity links.

Moreover, except for the voice communications which is more persistent, the needs for communication sessions by some crewed activities during Mars surface missions are less deterministic or even opportunistic. The UIS, therefore, would provide more responsive support for their mode of operations. Other scenarios that might benefit from the UIS mode are:

- A small satellite could fly its mission and signal for relay services only when it has enough power to do so.
- Small landed missions could signal for relay services at a preferred time of day or burst data after it has been collected.

A net-lander mission might signal for relay services only when it has detected relevant events.

6. Lunar Relay Orbiters

6.1. Lunar Relay Orbiters (2018-2030)– Key Attributes

During the timeframe of 2018 – 2030, there will be at least four Lunar relay orbiters in service: The Lunar Gateway (NASA), Lunar Communications Pathfinder (ESA/SSTL/Goonhilly), Chang'e-4 Queqiao (CNSA), and Chandayaan-2 orbiter (ISRO). For each relay orbiter, the following key attributes are summarized in Table 8:

- Relay orbit type
- Relay orbital parameters

- Relay coverage performance
- Frequency bands to be used for relay-Earth link and proximity link
- Maximum data rates achievable for relay-Earth link and proximity link
- Space data link protocols for relay-Earth link and proximity link
- Space network protocol

When comparing the key attributes of the four relay orbiters, the following points may be worth noting:

Relay orbit type – Driven by their respective mission objectives, they all are designed to fly in different orbit. But all four orbits are S. Pole biased in favor of relay coverage to surface vehicles in S. Pole.

Relay cross support – Three of the four relay orbiters (i.e., excluding the Queqiao) are compatible with one another at physical layer as they are all designed with S-band for proximity link. Two of the three, i.e., the Lunar Gateway and Lunar communications Pathfinder, will be able to cross support each other's user missions through common interface at physical, data link, and network layers.

Relay coverage performance – Of the four Lunar relay orbiters, the Lunar Communications Pathfinder will be able to provide the best relay coverage performance to S. Pole surface vehicles due to its 12-hour frozen orbit, aka., the Todd Ely orbit.

High-rate trunk link – Only the Lunar Gateway will offer a high-rate trunk link via Ka-band (up to 30 Mbps forward link and at least 100 Mbps for return link) and optical capability (up to 1.0 Gbps). This is primarily driven by the projected link capacity for supporting human exploration activities.

High-rate proximity link – Only the Lunar Gateway will offer a high-rate proximity link via Ka-band (up to 30 Mbps forward link and at least 100 Mbps for return link) and optical capability.

Cross link between the four relay orbiters – Given the significantly different orbits, the establishment of cross link between any two of the four relay orbiters may not be possible unless the design of their flight paths are well coordinated and planned in advance.

Relay user base - Chang'e-4 Queqiao and Chandayaan-2 orbiter, by design, have limited their user bases to the lander and rover of their own respective missions. In contrast, the Lunar Gateway and Lunar Communications Pathfinder are projected to support wider user bases including user vehicles of other space agencies.

Space internetworking protocol – Only the Lunar Gateway and Lunar Communications Pathfinder will provide network layer capabilities based on the DTN protocol suite.

Table 8 Key Attributes of Lunar Relay Orbiters To Be Launched During 2018 – 2030 Period

Relay Orbiter	Launch Year	Agency	Earth communication assets	Orbit type	Orbital parameters	Coverage performance	Frequencies & Maximum Data Rates				Space data link protocol	Space network protocol	Relay Services
							Earth to Relay	Relay to Earth	Relay to Lunar surface or orbital user	Lunar surface or orbital user to Relay			
Lunar Gateway	2022	NASA	DSN, NEN, ESTRACK	Near-Rectilinear Halo Orbit (NRHO)	Orbital period: ~6.56 days. 3300 x 71,000 km adjustable orbit. Max range from S. Pole: 71,000 km. Max range rate as observed from S. Pole is 0.85 km/s.	Orbital period ~6.56 days. Continuous coverage of S.Pole for 144.6 hours with a gap of 5.4 hours	•X-band: 10 Msps; •Ka-band: at least 10 Mbps (may be 30 Mbps); •Optical: rate TBD	•X-band: 4 Msps; •Ka-Band: at least 100 Mbps (may be 300 Mbps) •Optical: rate TBD	•S-band: 10 Msps; •Ka-band: 10 Mbps; •Optical: rate TBD	•S-band: 4 Msps; •Ka-band: 100 Mbps; •Optical: rate TBD	•All links: AOS (USLP when CCSDS Blue Book is available)	DTN BP/LTP	Space internetworking service, In-situ tracking service, In-situ navigation service (TBC).
Lunar Communications Pathfinder	2022	Goonhilly/SSTL/ESA	Goonhilly, ESTRACK	Todd Ely Orbit: 12-hour Frozen Orbit	SMA = 6142.4 km. ECC = 0.6. INC = 57.7 deg. Argument of perilune = 90/270 deg. Elliptical 500 x 9,900 km orbit. Max range from S. Pole: ~9,900 km. Max range rate as observed from S. Pole is 0.68 km/s.	Orbital period 12 hours. Continuous coverage of S.Pole for 9.13 hours with a gap of 2.87 hours.	•X-band: 16 Kbps	•X-band: 3 Mbps	•S-band and/or UHF: 64 Kbps	•S-band and/or UHF: 2 Mbps	•Relay-User links: USLP and/or Proximity-1; •Earth-Relay links: USLP and/or TC/TM	DTN BP/LTP	Space internetworking service, In-situ tracking service, In-situ navigation service (TBC).
Chang'e-4 Queqiao	2018	CNSA	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina)	Earth-Moon L2 Halo Orbit	14-day Halo orbit at Earth-Moon L2. Max range from S. Pole: 84,000 km.	At S. Pole, 1 contact/14 days with duration of 224 hours, followed by a gap of 102 hours.	•S-band: 1 Kbps	•S-band: 2 Mbps	•X-band: 1 Kbps	•X-band: 4x256 Kbps	•Relay-User links: Proximity-1 (TBC); •Earth-Relay links: TC/TM	None (TBC)	Store-&-forward space packet service

Chandrayaan-2 Orbiter	2019	ISRO	IDSN, DSN	Lunar Circular Orbiter	100 x 100 km circular orbit. Range from S. Pole: 100 km.	Orbital period: 2 hours	•S-band: 125 bps	•S-band: 4 Kbps; •X-band: 8.4 Mbps (payload data)	•S-band: 2 Kbps	•S-band: 2 Kbps; •X-band: 256 Kbps (payload data)	•Relay-User links: Proximity-1 (TBC); •Earth-Relay links: TC/TM	None	Store-&-forward space packet service
For Chandrayaan-3 lander, Chandrayaan-2 -Orbiter is relay orbiter	2022	ISRO	IDSN, DSN	Lunar Circular Orbiter	100 x 100 km circular orbit. Range from S. Pole: 100 km.	Orbital period: 2 hours	•S-band: 1 kbps	•S-band: 1 Kbps; •X-band: 8.4 kbps (payload data)	•S-band: 8 Kbps	•S-band: 10 Kbps;	•Relay-User links: Proximity-1 (TBC); •Earth-Relay links: TC/TM	None	Store-&-forward space packet service

6.2. Lunar Relay Orbiters – Coverage Analysis

As shown in the Lunar communications architecture depicted in Figure 1, the existence of a Lunar relay network is a key aspect of the architecture. While at present there are many unknowns about the profile of the future user missions of the relay network (even beyond the 2018-2030 timeframe), it is crucial for the IOAG to understand the coverage performance, the most important attribute, of the currently planned Lunar relay orbiters. And beyond that, the IOAG should define the Lunar relay network in terms of its orbital characteristics. For that reason, this section includes a coverage analysis for each of the four relays listed in Table 8:

- Lunar Gateway - Near-Rectilinear Halo Orbit (NRHO)
- Lunar Communications Pathfinder – 12-Hour Frozen Orbit (Todd Ely Orbit)
- Chang'4 Queqiao - 14-day Southern Halo Orbit at Earth-Moon L2
- Chandrayaan-2 Orbiter – Lunar Circular Orbit

For these relay orbiters, their coverage performance, based on simulation and modeling results (in graphs) generated by Charles Lee and Kar-Ming Cheung, are summarized in Sections 6.3 – 6.6. In addition, a Lunar relay constellation, as an "ideal" solution to the relay network, is addressed in Section 6.7. All coverage analysis and ground visibility modeling use a minimum elevation angle of 10 degree to account for the local horizon mask.

6.3. Lunar Gateway - Near-Rectilinear Halo Orbit (NRHO)

The coverage performance of Lunar Gateway can be summarized as follows based on a notional NRHO[19] orbit:

- Covers most of lunar far-side, except the far-side center
- Favors the far side S. Pole
- Contact every 6.35 days
- Range from Lunar South Pole can be 10,000-70,000 km
- Latitudes below 60-deg South gets 6+ days of contact per 6.35 days
- Communication gaps at Lunar South Pole is no more than 6 hours per cycle
- S. Pole has no or low visibility with Earth, and has to rely on relay orbiter
- An additional ground station in S. Hemisphere (e.g. Hartebeesthoek, S. Africa) helps to eliminate the daily short gaps

Figure 7 Lunar Gateway NRHO - View & Range from Lunar South Pole

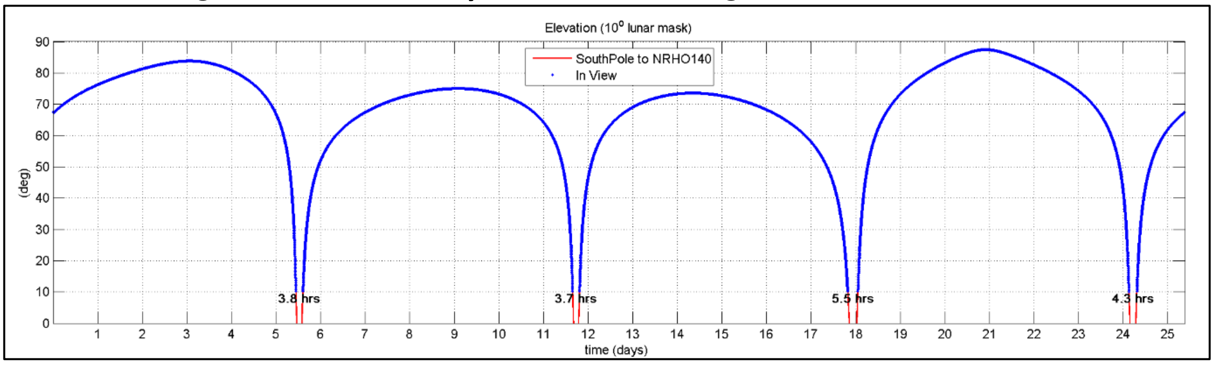
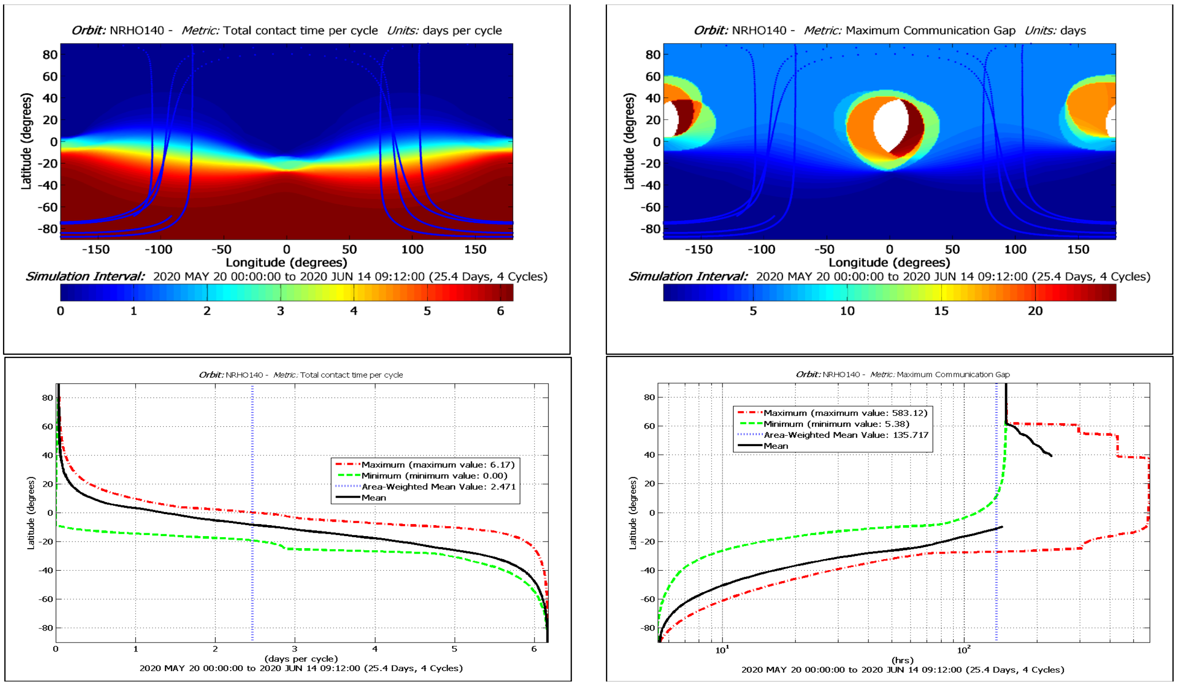


Figure 8 Lunar Gateway NRHO - Global Lunar Surface Contacts



6.4. Lunar Communications Pathfinder – 12-Hour Frozen Orbit (Todd Ely Orbit)

The coverage performance of the Lunar Communications Pathfinder, ESA/SSTL/Goonhilly, can be summarized as follows based on a notional 12-hour frozen orbit[20, 21, 22]:

- Max range from S. Pole: ~9,900 km.
- Continuous coverage of S. Pole for 9.13 hours with a gap of 2.87 hours.
- Number of contacts per day: Maximum 2.04 (S.Pole), min 1.24, average 1.597
- Total contact time per day: Maximum 18.26 hours (S.Pole), min 0.43, average 6.836

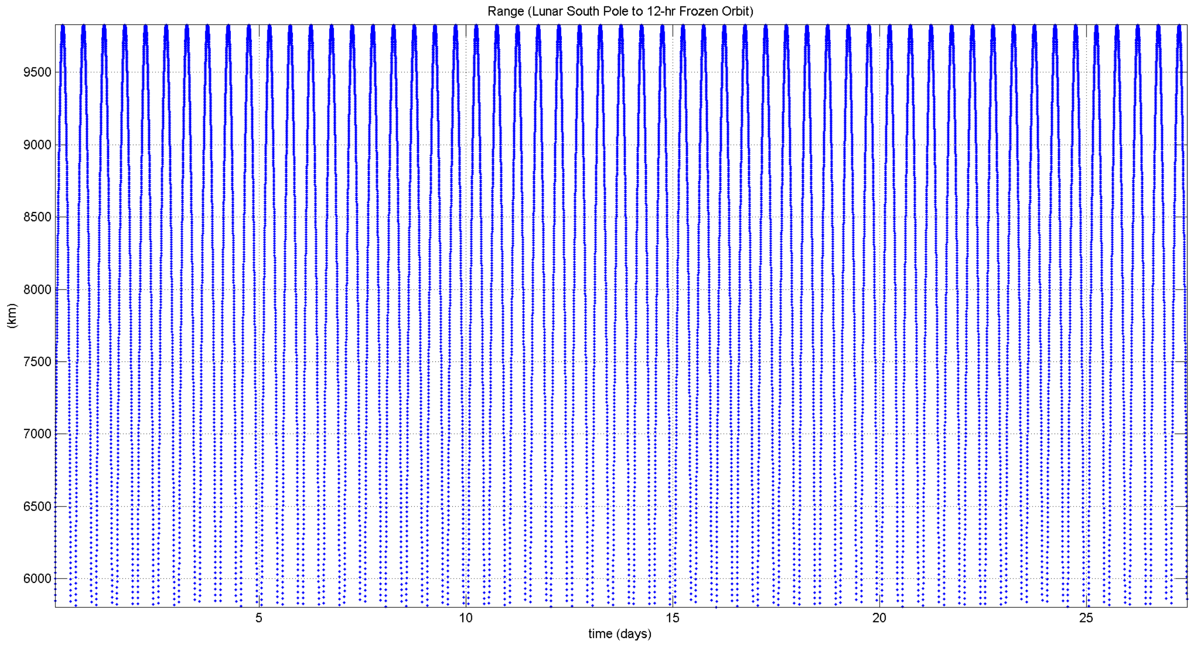


Figure 9 Lunar Communications Pathfinder - 12-Hour Frozen Orbit: In-View Range

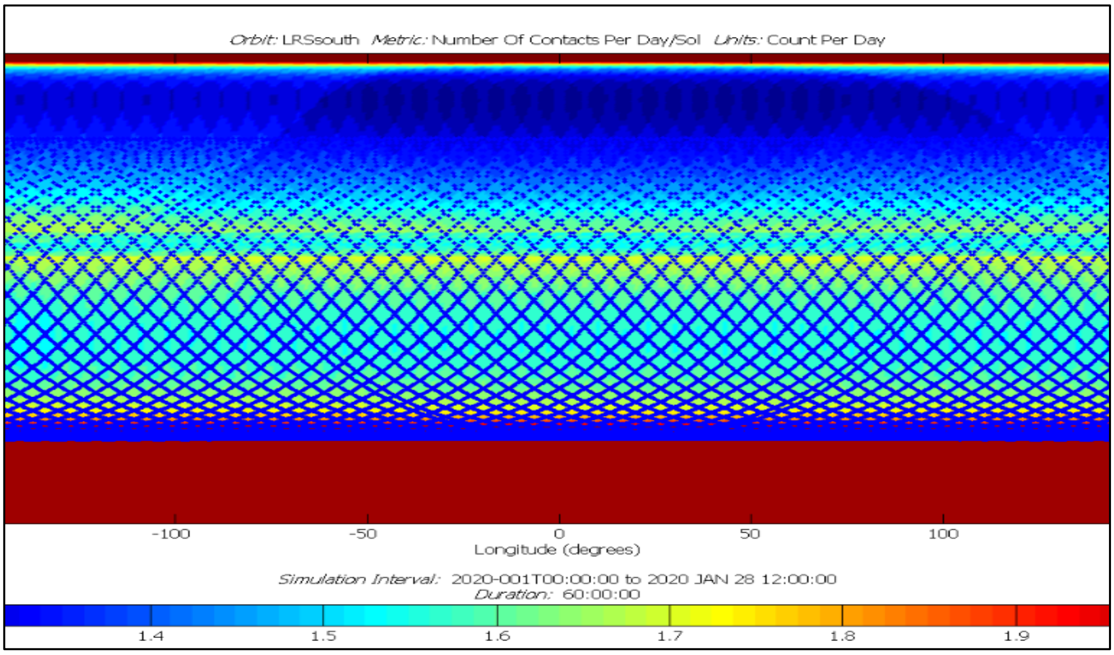


Figure 10 Lunar Communications Pathfinder - 12-Hour Frozen Orbit: Contacts Per Day

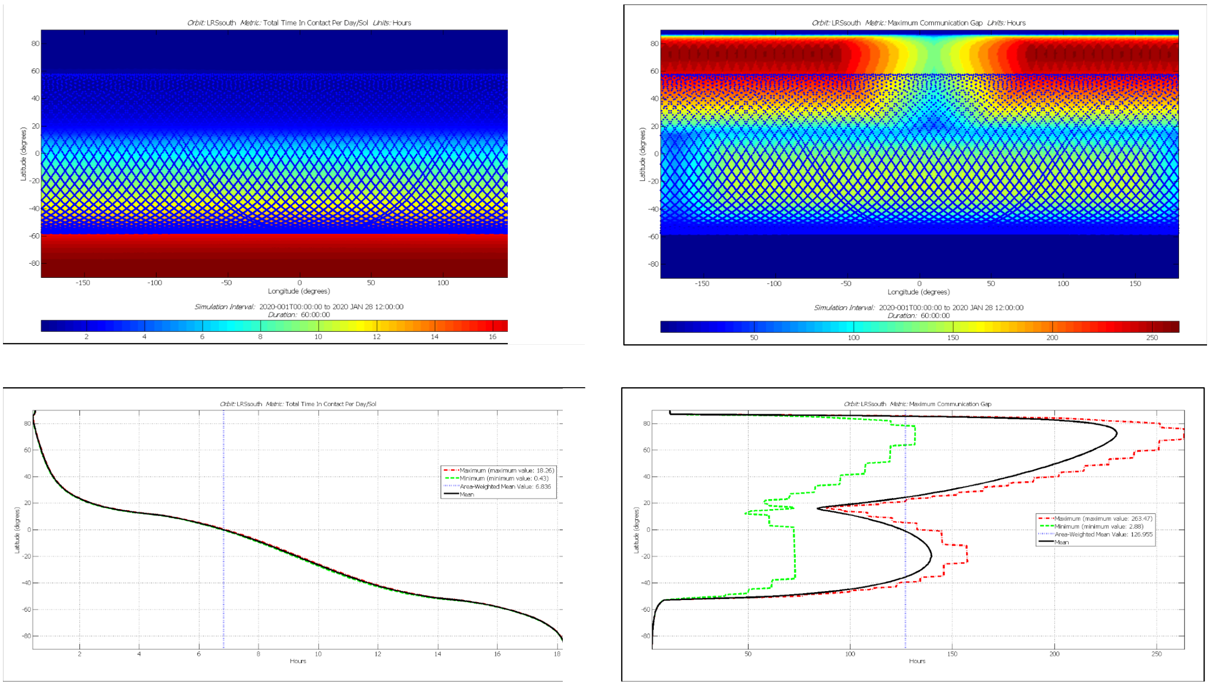


Figure 11 Lunar Communications Pathfinder - 12-Hour Frozen Orbit Contact Time & Communication Gap

6.5. Chang'4 Queqiao - 14-day Southern Halo Orbit at Earth-Moon L2

The coverage performance (to South Pole surface vehicles) of the Chang'4 Queqiao, by CNSA, can be summarized as follows based on a notional Halo Orbit[23] at Earth-Moon L2:

- Max range from S. Pole: 84,000 km.
- At S. Pole, 1 contact/14 days with duration of 224 hours, followed by a gap of 102 hours.

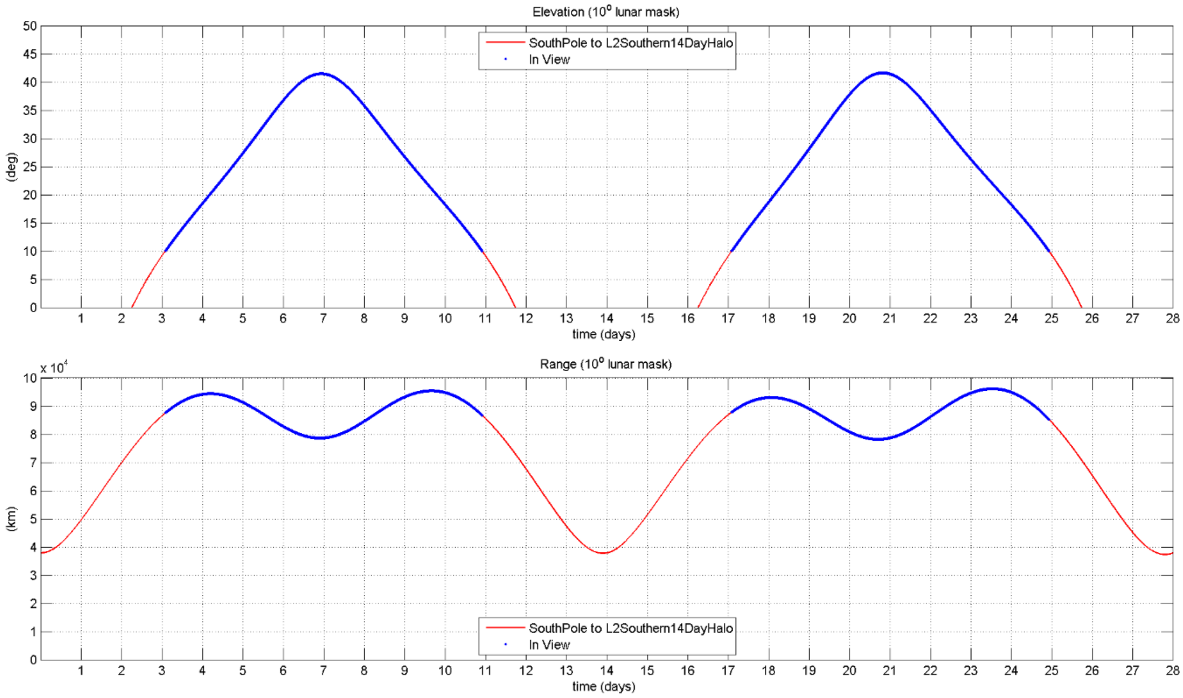


Figure 12 Chang'4 Queqiao – Earth-Moon L2 Halo: Lunar South Pole In-View Range

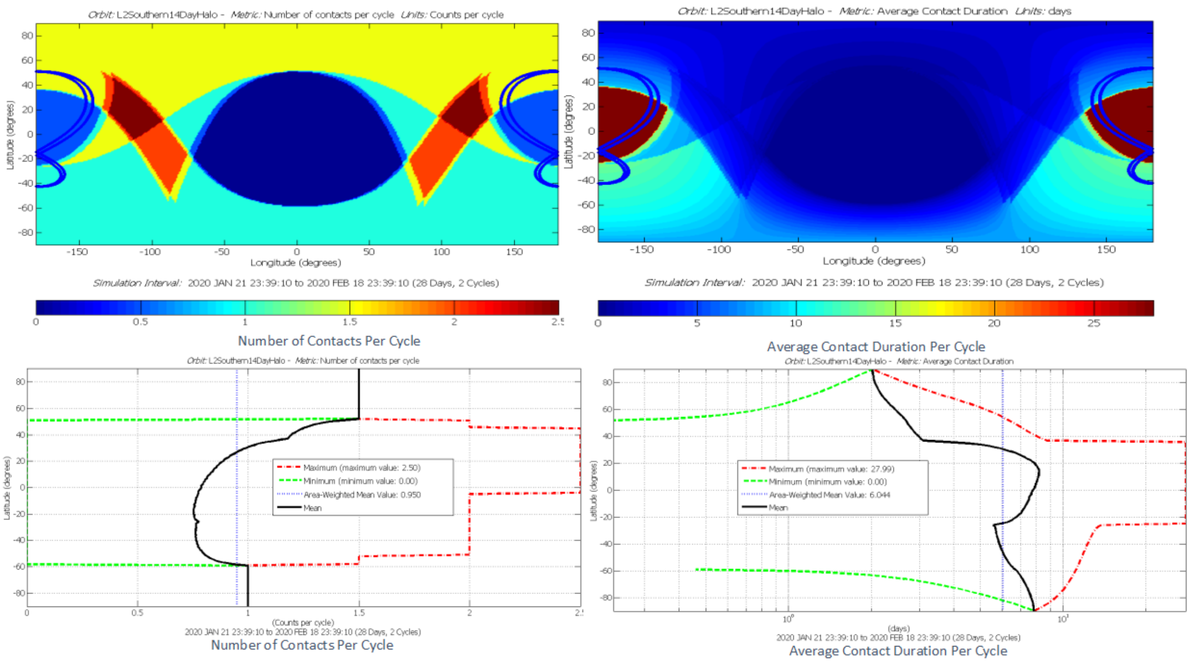


Figure 13 Chang'4 Queqiao – Earth-Moon L2 Halo: Contacts per 14-Day Cycle

6.6. Chandrayaan-2 Orbiter – Lunar Circular Orbit

The coverage performance of the Chandrayaan-2 orbiter, by ISRO, can be summarized as follows based on a notional Lunar circular orbit (the maximum values below apply to South Pole surface vehicles):

- The orbit altitude from S. Pole is 100 km.
- Number of contacts per day: Maximum 12.23 (S. Pole), minimum, 1.83, average 2.949
- Contact duration: Maximum 0.15 hour, minimum 0.10 hour, average 0.12 hour
- Total contact time per day/sol: Maximum 1.87 hours (S. Pole), minimum 0.22 hour, average 0.355 hour

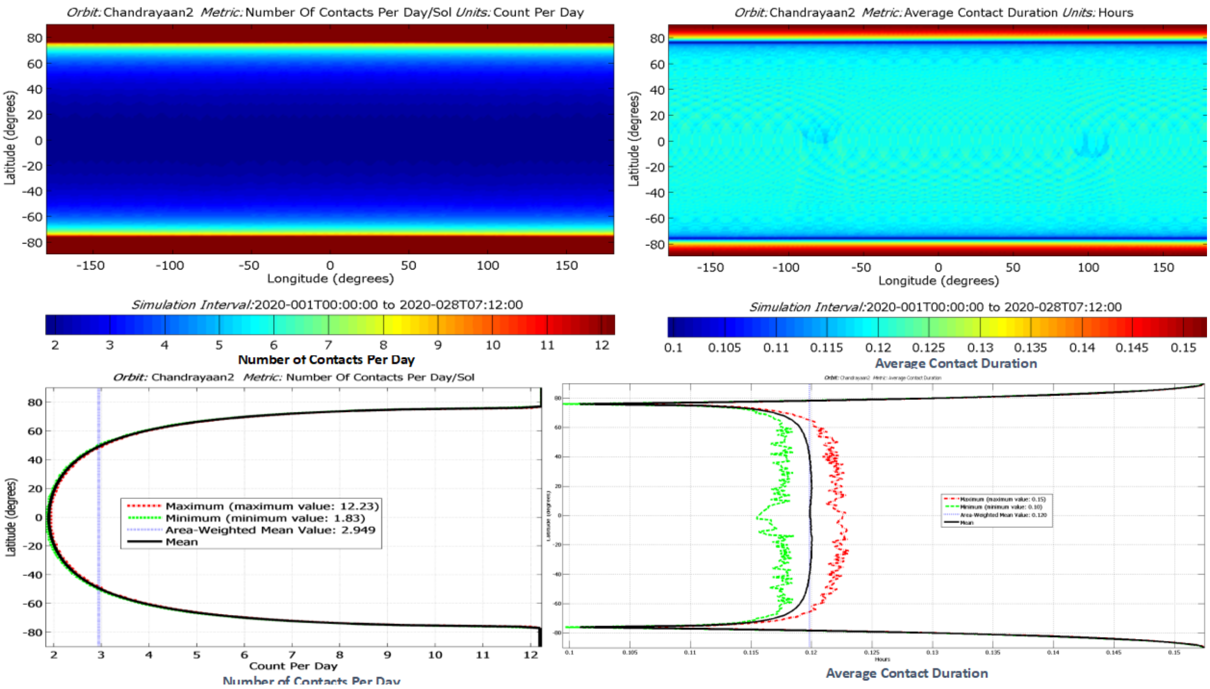


Figure 14 Chandrayaan-2 Orbiter – Lunar Circular Orbit: Contacts per 2-Hour Cycle

6.7. The "Ideal" Lunar Relay Constellation

During the past few years, a few studies were conducted to understand the various lunar relay orbits and assess their coverage performance. The Moon, as Earth's satellite, is unique in the following ways:

- Due to tidal locking, the Moon rotates 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, and those in polar regions have intermittent coverage. The landed space vehicles on the far side would have to rely on a relay orbiter to communicate with Earth.
- Due to the proximity of the Moon with Earth, Earth's ground stations can cover the nearside of the lunar surface.

For lunar relay orbits with coverage biased towards the far side of the moon, the slow rotating rate of the Moon proves to be a formidable challenge. They tend to be either unrealizable, too unstable, or too far from the lunar surface to be useful. As a result, the lunar relay constellations that provide global coverage of the Moon must meet the following criteria:

- Orbits should be stable to minimize delta-V required for station keeping.
- Range between an orbiter and a lunar surface element should be small to minimize space loss in communications.
- Provide high average contact duration across all latitudes.
- Support high percentage of contact time across all latitudes.
- Minimize maximum gap time across all latitudes.
- Allow a viable evolution path to support upcoming lunar mission concepts.

This has led to an “ideal” satellite constellation flying on a combination of circular orbits and elliptical orbits[24, 25]:

- a 12-hour frozen elliptical orbit with its line of apsides librating over the North Pole
- a 12-hour frozen elliptical orbit with its line of apsides librating over the South Pole
- a 12-hour circular elliptical orbit around the equator

The Keplerian elements of the three orbits are summarized in Table 9. The orientations and trajectories of the lunar relay constellation are illustrated in Figure 15.

Table 9 Summary of Keplerian Elements of the Lunar Orbits

Lunar Satellite Orbits	Semi-major Axis (km)	Eccentricity	Inclination (°)	Ascending Node (°)	Argument of Perilune (°)	True Anomaly (°)
12-hr circular equatorial	6142.4	0	0	0	315	adjustable
12-hr elliptical North	6142.4	0.6	57.7	270	270	adjustable
12-hr elliptical South	6142.4	0.6	57.7	0	90	adjustable

The maximum range for a lunar surface element to communicate with an orbiter in the circular orbit is 5892 km, and 9672 km with an orbiter in the elliptical orbit. The average contact time duration, the total contact time per day, and the maximum gap time as a function of latitude are given in **Figure 16**, **Figure 17** and **Figure 18** respectively.

This “ideal” lunar relay constellation would be comprised of 3 to 5 orbiters. For the maximum deployment scenario, the constellation would include:

- Two relay orbiters on the 12-hour frozen elliptical orbits with its line of apsides liberating over the North Pole
- Two relay orbiters on the 12-hour frozen elliptical orbits with its line of apsides liberating over the South Pole
- One relay orbiter on 12-hour circular orbit around the equator

The advantages of this constellation are:

- This constellation is scalable – launching one relay to meet initial needs and adding relays as number of missions increase.
- The constellation can be built up incrementally, e.g., S. Pole first, Equator, and finally N. Pole.
- The constellation offers good and relatively even coverage at different latitude
  - Long contact duration (5 – 7 hours)
  - Large total contact time per day (17.6 – 19.4 hours)
  - Short gap time (1.4 – 5.8 hours)

The downside, however, is it requires launching multiple satellites into orbits.

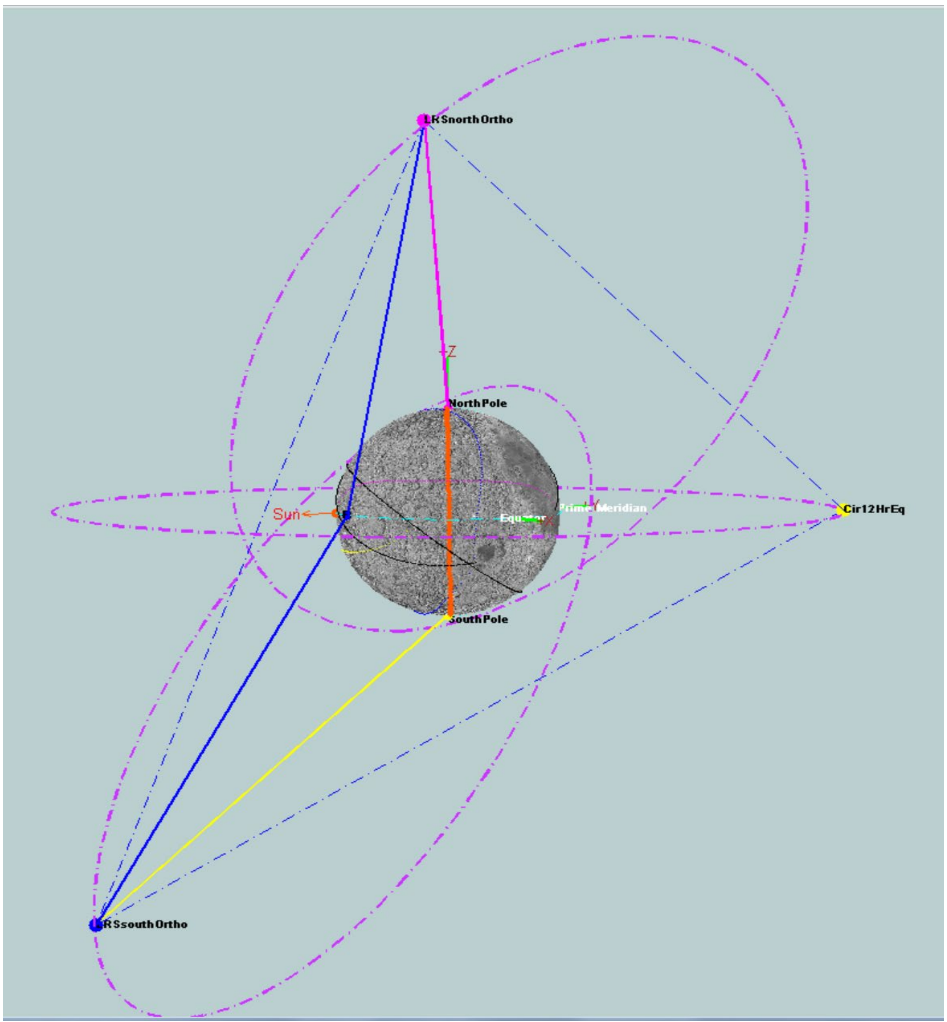


Figure 15 Lunar Relay Constellation – The "Ideal" Orbits

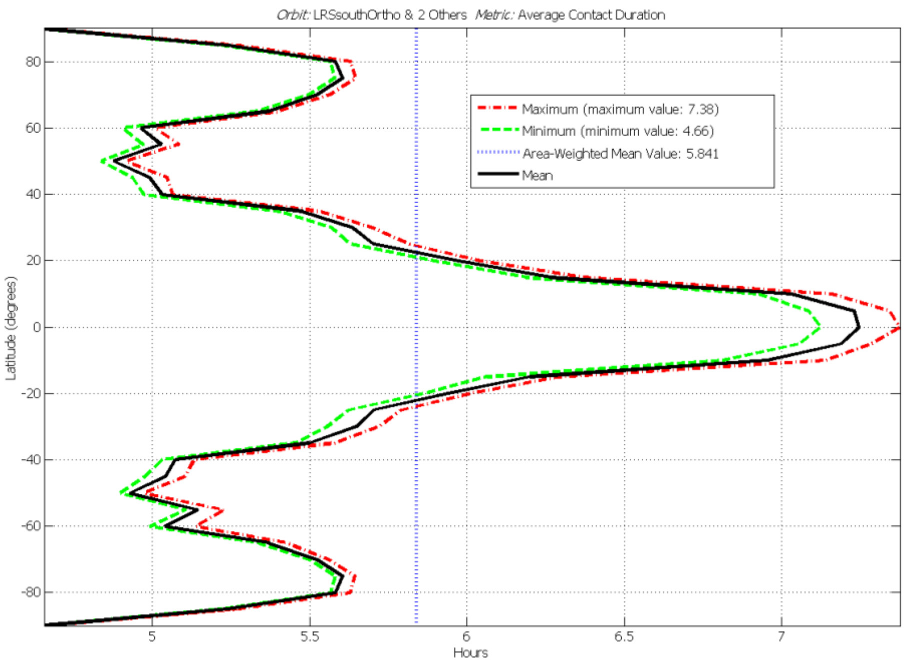


Figure 16 Average Contact Time Duration - The "Ideal" Constellation

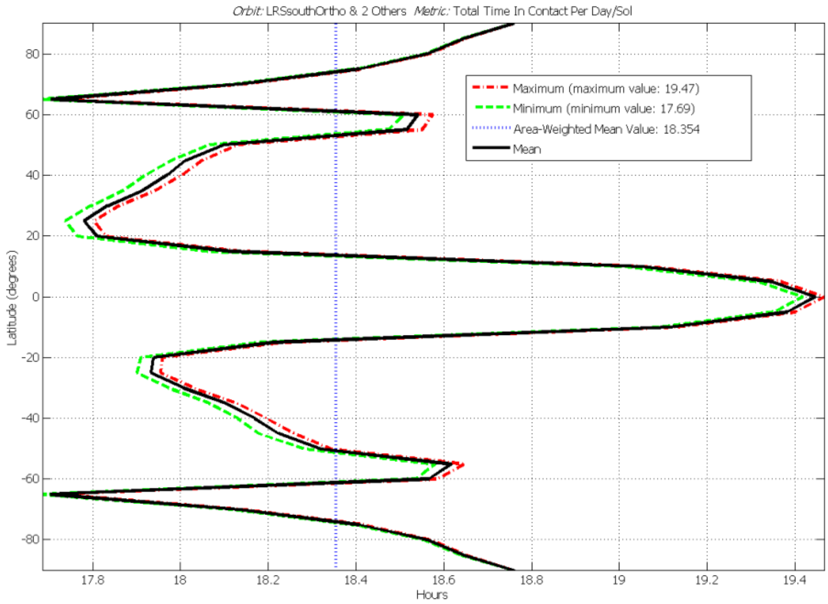


Figure 17 Total Contact Time Per Day (hours) – The "Ideal" Constellation

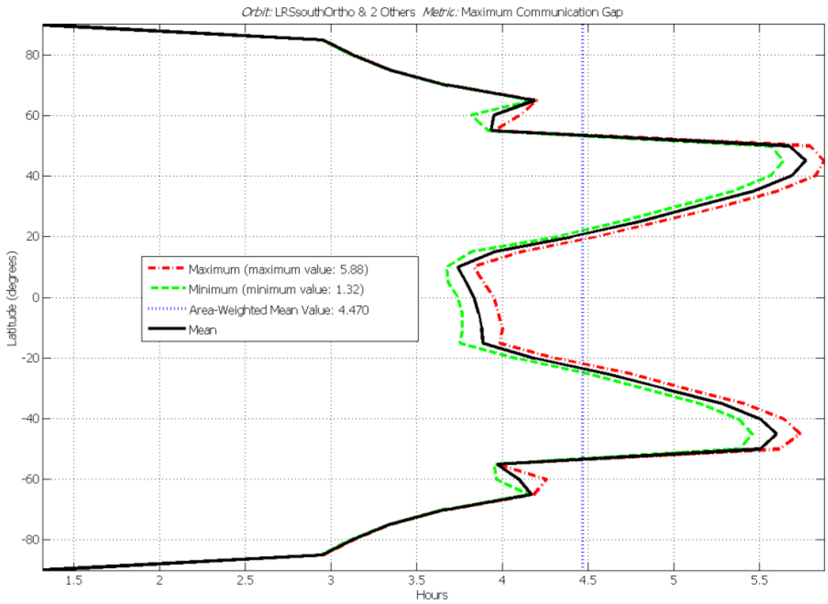


Figure 18 Maximum Gap Time - The "Ideal" Constellation

7. Conclusions and Recommendations

The following are the conclusions and recommendations from the study:

- We have reached consensuses on the selected **frequency, modulation, coding, and ranging schemes** plus the space data link and network layer protocols for the future Lunar communications architecture.

- We have defined a conceptual Lunar communications architecture that features a Lunar space internet encompassing the Lunar relay network, Lunar surface network, and Earth network.

- In the era of 2020s, for the Lunar relay network, the **USLP** will offer the ability to interoperate by multiple relay orbiters at the data link layer. Space Internetworking-over-**DTN** further will allow them to interoperate at the network layer.
    - At least two relay orbiters are on the same path towards provision of relay data services.
- In the era of 2020s, the adoption of S-band for proximity link by multiple relay orbiters would enable the **in-situ tracking service and possibly the in-situ navigation** (GPS-light or Galileo-light capability).
    - At least three relay orbiters could serve as a navigation satellite constellation to support the S. Pole surface vehicles.
- Ultimately, for the future international Lunar exploration at a global scale, the IOAG may want to coordinate with its member agencies to **incrementally build up a lunar network**.
    - This is particularly meaningful for regions of high user population density, e.g., South Pole and far side.
- We have defined a set of Lunar relay services and a few key attributes, i.e., relay method, relay access mode, and relay service initiation mode.
    - Over the relay proximity link, **multiple access and user-initiated service mode per service acquisition protocol** will be essential for achieving cost-effective operations in international Lunar exploration.

Acknowledgments

The authors thank the IOAG including the chief delegates of its member agencies for endorsing the study on the Lunar Communications Architecture. Their strong advocacy in furthering the international collaboration for space exploration is greatly appreciated. Needless to say, it is with the endorsement by the management of ASA, ASI, CNES, CNSA, CSA, DLR, ESA, ISRO, JAXA, KARI, NASA, ROSCOSMOS, and UK Space Agency, that has made this working group effort possible. Part of the contribution to this effort by NASA was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the NASA.

The information presented about future lunar missions is pre-decisional and is provided for planning and discussion purposes only.

Appendix A: List of Acronyms

AES-GCM	Advanced Encryption Standard (AES) in Galois/Counter Mode (GCM)
AOS	Advanced Orbiting Systems
ASI	Agenzia Spaziale Italiana
BCH	Bose-Chaudhuri-Hocquenghem
BPSK	Binary Phase Shift Keying
BSP	Bundle Security Protocol
CCSDS	Consultative Committee for Space Data Systems
CDMA	Code Division Multiple Access
CLTU	Command Link Transmission Unit
CNES	Centre National d'Etudes Spatiales
CSA	Canadian Space Agency
CSTS	Cross Support Transfer Service
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSG	Deep Space Gateway (renamed to LOP-G)
DTN	Disruption Tolerant Network
ESA	European Space Agency
ESOC	European Space Operations Centre
FCMLP	Frequencies, Coding, Modulations, and Link protocols
FDMA	Frequency Division Multiple Access
GMSK	Gaussian Minimum Shift Keying
GSFC	Goddard Spaceflight Center
HQ	Headquarters
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPSec	IP Security Protocol
IOAG	Interagency Operations Advisory Group
ISECG	International Space Exploration Coordination Group
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KARI	Korea Aerospace Research Institute
LAN	Local Area Network
LCAWG	Lunar Communications Architecture Working Group
LDPC	Low-Density Parity-Check
LEO	Low Earth Orbit
LOP-G	Lunar Orbiting Platform – Gateway, often called Lunar Gateway or Gateway
LTE	Long Term Evolution
MOC	Mission Operations Center
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NTIA	National Telecommunications and Information Administration (USA)
OQPSK	Offset Quadrature Phase-Shift Keying
P2P	Point-to-Point
PCM	Pulse Code Modulation
PM	Phase Modulation
PN	Pseudo Noise
PNT	Position, Navigation and Timing

PPM	Pulse-Position Modulation
PSK	Phase Shift Keying
SBSP	Simple Bundle Security Protocol
SCPPM	Serially Concatenated Pulse-Position Modulation
SDLS	Space Data Link Security Protocol
SFCG	Space Frequency Coordination Group
SLE	Space Link Extension
SQPSK	Staggered Quadrature Phase-Shift Keying
SZM	Shielded Zone of the Moon
TC	Telecommand
TCP	Transmission Control Protocol
TM	Telemetry
UDP	User Datagram Protocol
USLP	Unified Space Link Protocol
VCM	Variable Coded Modulation
WG	Working Group
WLAN	Wireless Local Area Network

Appendix B: References

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