The Lunar Space Communications Architecture From The KARI-NASA Joint Study

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The Lunar Space Communications Architecture From The KARI-NASA Joint Study

- Purpose of the paper
  - The paper covers the lunar space communications architecture defined by the feasibility study jointly conducted by the KARI and NASA.
  - The paper covers lunar communications architectures for the 2018-2021 timeframe and, beyond that, the 2016-2025 era.
- Objective of the joint KARI-NASA activity
  - To establish a a formal space communications architecture for the Korea Pathfinder Lunar Orbiter (KPLO) and subsequent lunar exploration missions that KARI will undertake during the next decade.
  - The architecture is to facilitate the evaluation of the feasibility of cross support in space communications between KARI and NASA.
- Background
  - A KARI-NASA interagency agreement on conducting a feasibility study about potential lunar robotic cooperation was signed on 2 July 2014.
  - The joint feasibility study was conducted during October 2014 – April 2015. Concluded that the cross support in space communications and navigation between the two agencies would be feasible and mutually beneficial.

Lunar Missions To Be Launched During The Decade 2015 -2025

Mission	Launch Year	Agency	# of Vehicles	Mission Type
Chandrayaan-2	2017/2018	ISRO	3	Orbiter/lander/rover
Chang'e 4	2018	CNSA	2	Lander/rover
Chang'e 5	2017	CNSA	2	Orbiter/rover for sample return
Chang'e 6	2020	CNSA	2	Orbiter/rover for sample return
KPLO	2018	KARI	1	Orbiter
Korean Lunar Mission	2021	KARI	3	Orbiter/lander/rover
Luna 25	2024	RFSA	1	Lander
Luna 27	2020	RFSA	1	Rover
Luna 26	2020	RFSA	1	Orbiter
SLIM	2020	JAXA	1	Lander
Resource Prospector*	2020	NASA	2	Lander/rover
Lunar Communications Pathfinder*	2020s	ESA	1	Relay Orbiter

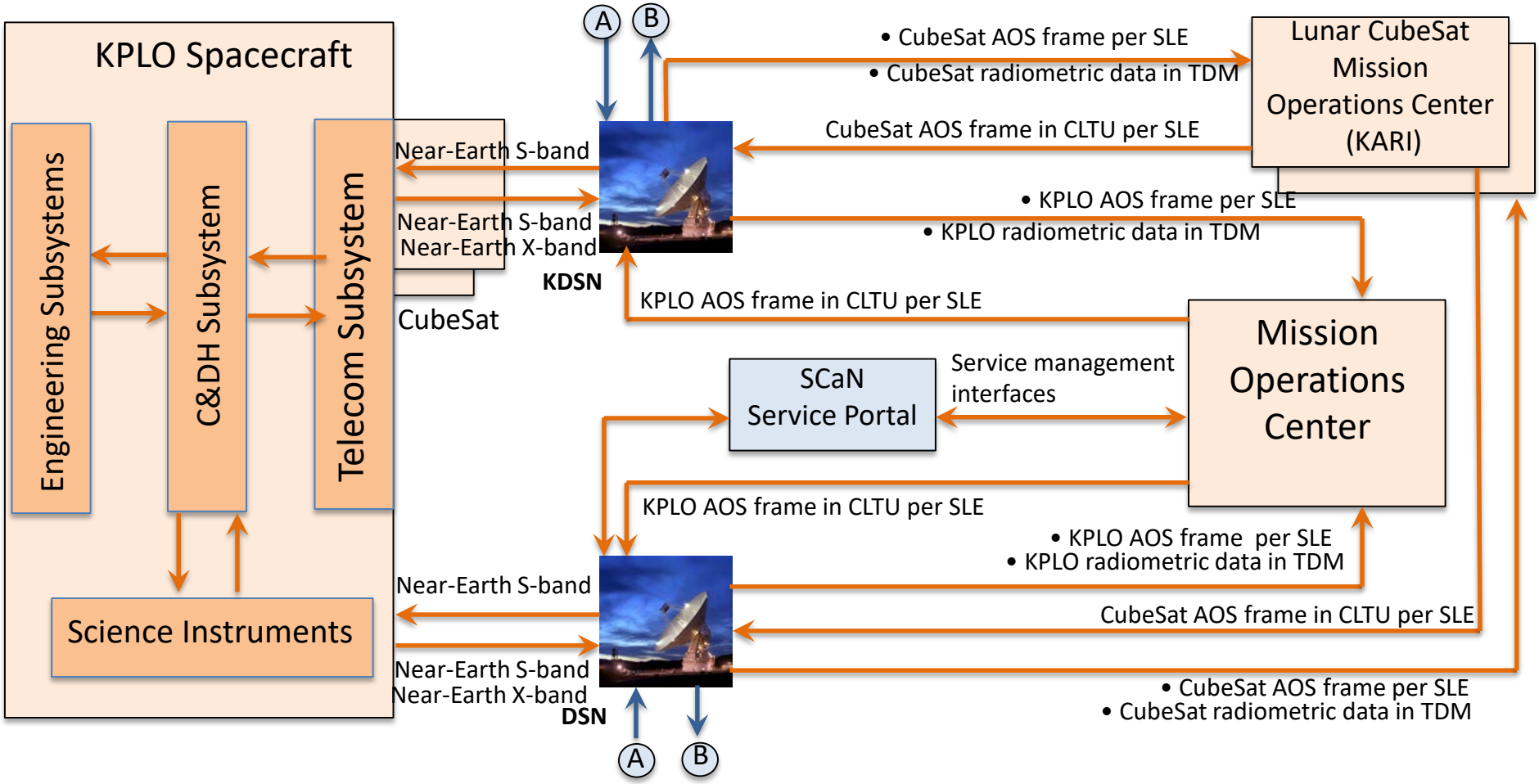
Note: All launch years are subject to further confirmation.
Note: *Mission in planning only, not yet approved or manifested.

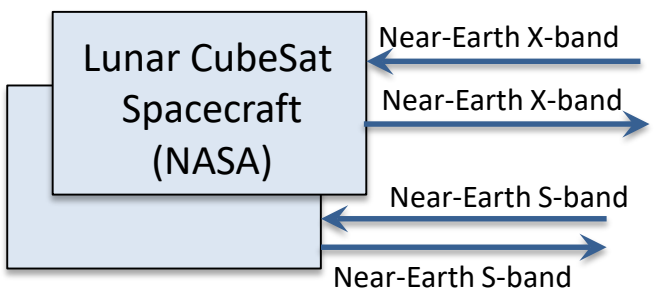
Lunar Missions To Be Launched During The Decade 2015 -2025

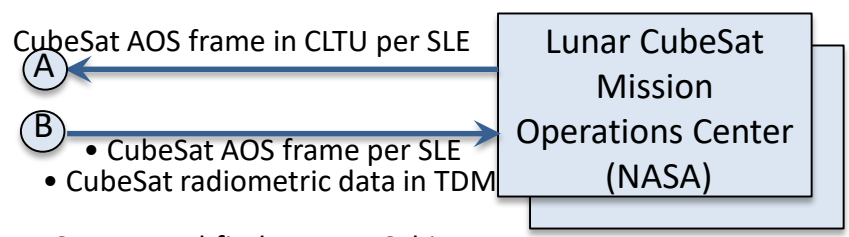
Mission	Launch Year	Agency	# of Vehicles	Mission Type
EM-1**	2018	NASA	1	Orbiter
EM-2**	2023	NASA	1	Orbiter
Lunar Flashlight	2018	NASA	1	CubeSat Orbiter
Lunar IceCube	2018	NASA	1	CubeSat Orbiter
Lunar H-Mapper	2018	NASA	1	CubeSat Orbiter
ArgoMoon	2018	ASI	1	CubeSat Orbiter
Omotenashi	2018	JAXA	1	CubeSat Lander
EQULLEUS	2018	JAXA	1	CubeSat Orbiter

Note: ** Not exactly a lunar mission; rendezvous to the Distant Retrograde Obit (DRO)

KARI-NASA Space Communications Architecture
Standard Services for Cross Support to KPLO & Other Lunar Missions



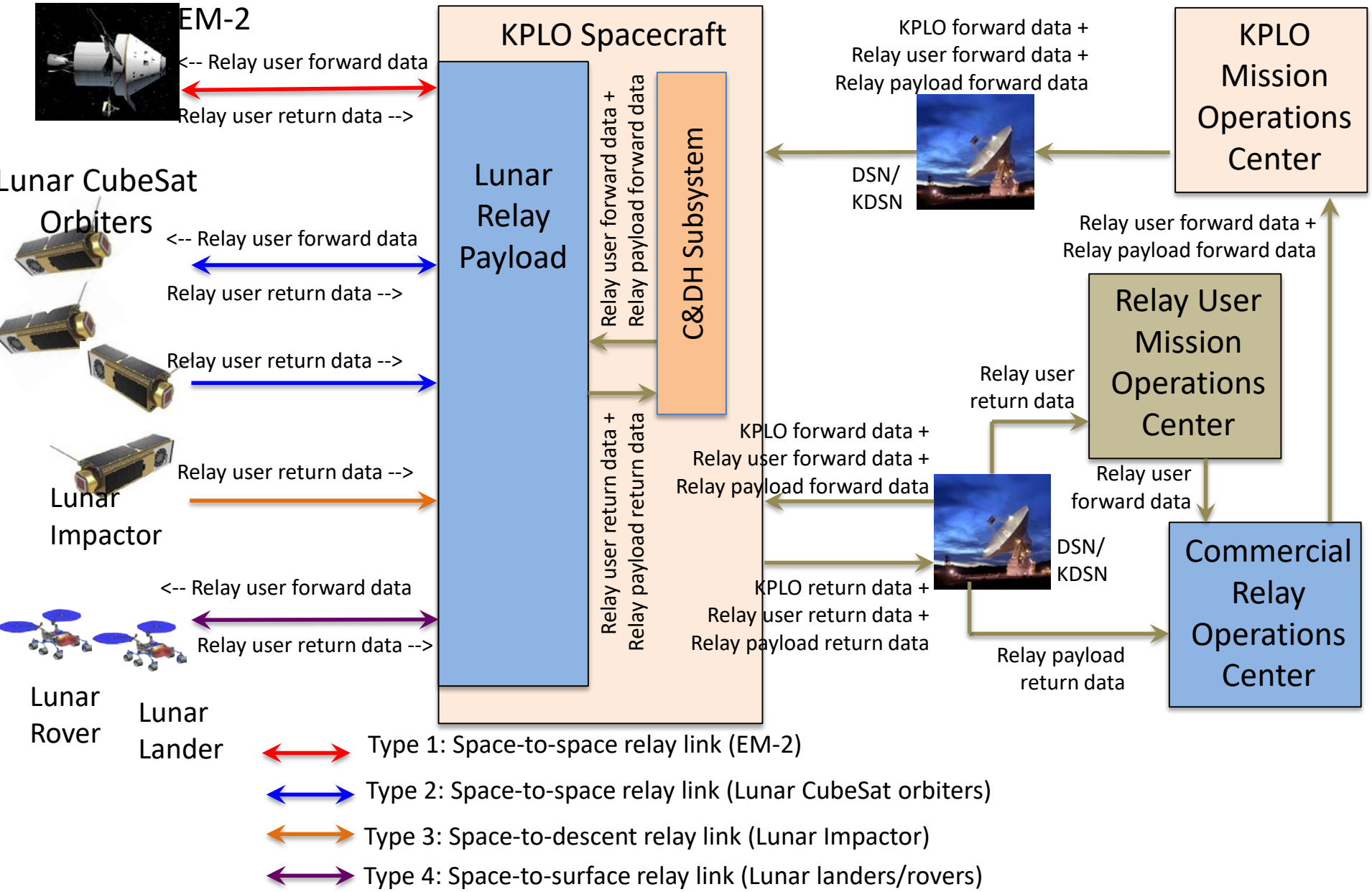




KPLO: KARI Pathfinder Lunar Orbiter
KDSN: Korean Deep Space Network
SCaN: NASA Space Communications & Navigation

Pre-Decisional Information -- For Planning Purposes Only

KARI-NASA Lunar Space Communications Architecture
Assessment of KPLO Providing Lunar Relay Services



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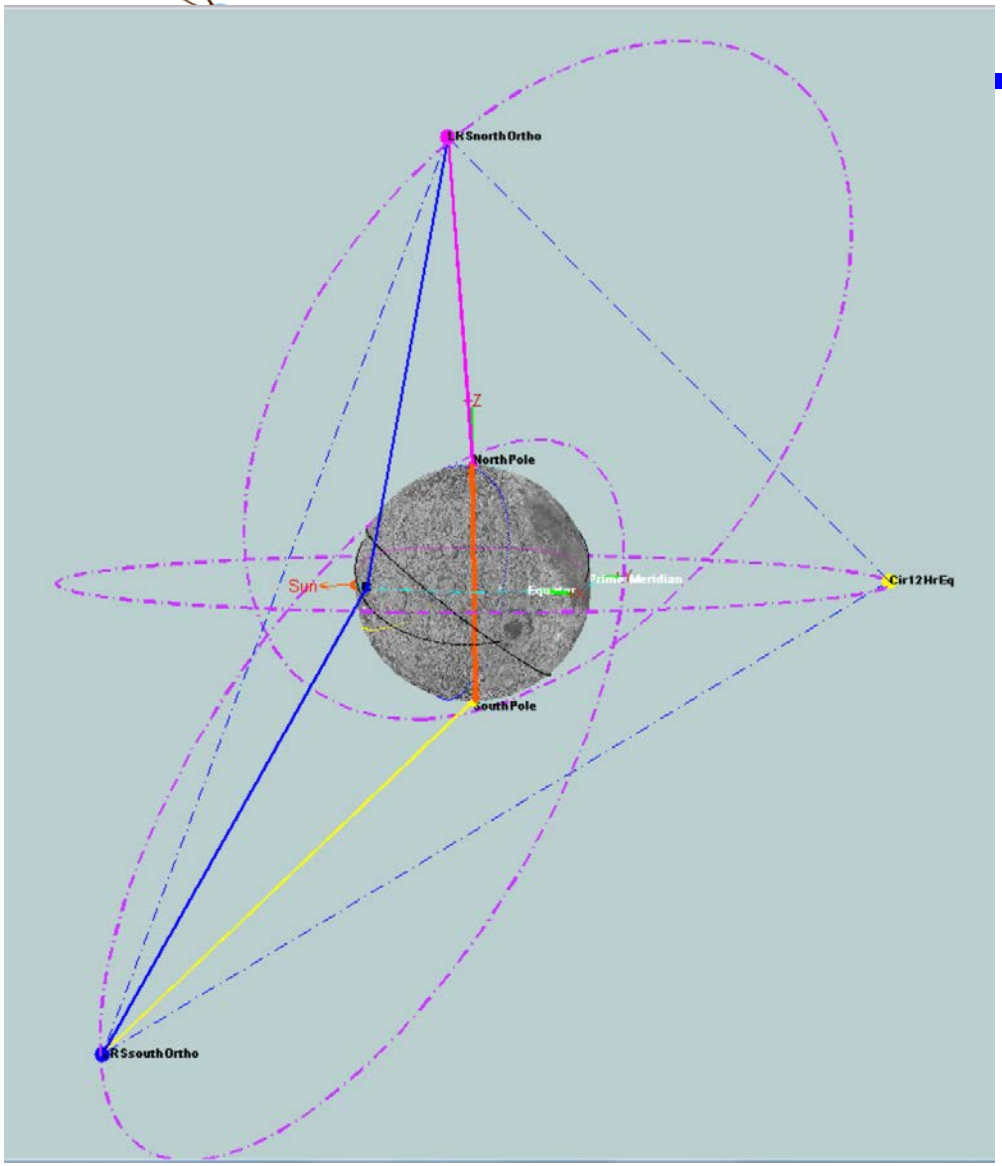
Lunar Space Communications Architecture Attributes – Progression Into A New Decade --

Attributes	Current – 2025 era	2026 – 2035 era
Connectivity & topology	Largely point-to-point, some limited relay.	A mix of point-to-point and network-layer connectivity.
Data rates	Return data: Maximum ~ 125 Mbps. Forward data: Maximum ~ 4 Kbps.	Return data: Maximum ~ 300 Mbps. Forward data: Maximum ~ 250 Kbps.
Multiplicity of space data link protocols	By directionality & user regimes - CCSDS TC/TM/AOS and Proximity-1 protocols.	Unified Space Link Protocol (USLP); a single protocol across the entire international "network" of communication assets.
Service levels	Space communications services at data link layer and below; radiometric observables over Moon-Earth link.	Data link-, network-, transport-, and file-layer services; end-to-end service involving multi-nodes; radiometric observables over Moon-Earth link and proximity link. On-board autonomous position determination.
Service management	Agency-specific and/or asset-specific approaches for service requests, planning & scheduling, and asset monitor & control.	International standard service management for service requests, planning & scheduling, & monitor & control.

Lunar Network
Challenges of Lunar Relay & Analysis Approach

- The near-side of Moon can be covered by Earth ground stations
- Due to tidal locking, Moon is rotating at the same rate as its revolution (27.3 days)
- Originally tried to find lunar orbits that favors the back-side, but not possible
  - An elliptical orbit with longitude of ascending node precessing at Moon's rotation rate, but any orbit of this kind would have a periapsis less than the Moon's radius
  - A geostationary orbit will have the radius about 88413 km, which is further than the Hill gravity-influence sphere (20 – 30K km for the moon), thus far and unstable
  - A halo orbit at Earth-Moon L2; but this type of orbit is far from the lunar surface (~64K km), and is highly unstable and requires much delta-V to maintain
- Thus the only reasonable orbit options are either circular orbits, or frozen elliptical orbits that favor the poles (constant argument of periapsis)
- We investigate various combinations of circular and elliptical orbits to form different relay network candidates, trading off between contact time and gap time.

Lunar Network
Proposed Lunar Relay Network of 3 Orbiters



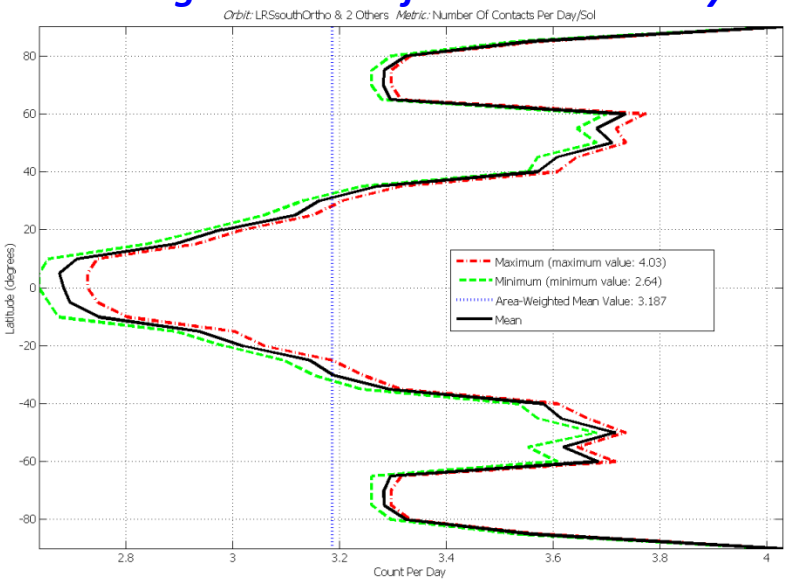
Constellation of 3 relay orbiters; one 12-hour circular orbit at the equator, and two 12-hour elliptical frozen orbits:

- SMA = 6541.4 km
- Eccentricity = 0.59999
- Inclination = 57.7°
- Ascending Node = Orthogonal
- Perilune= 90° and 270°
- 12-Hour Orbits
- Frozen lunar orbit
- Stationary Eccentricity, Asc. Node and perilune/apolune line
- Orbiters are phased such that both are at apolunes at once.
- Circ12Hr is 4405.1 km in altitude

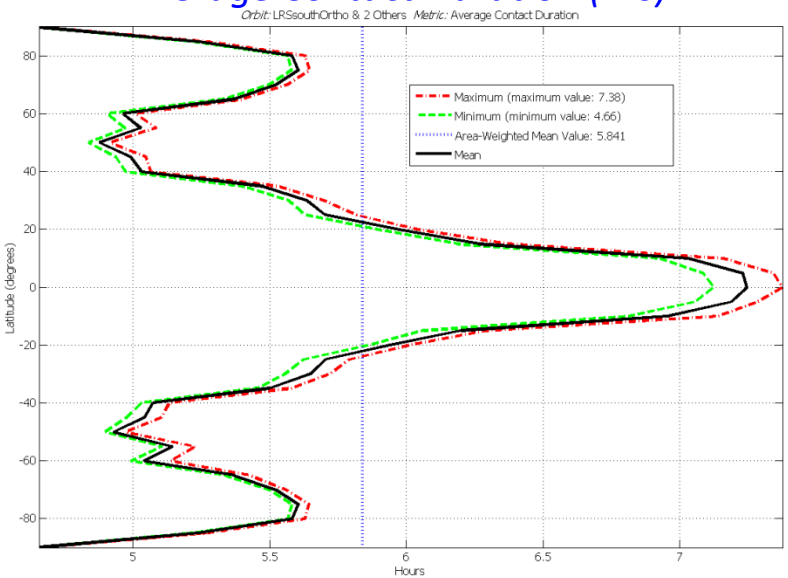
- Good trade-off between contact time and gap time
- Reasonable even coverage

Lunar Network
Constellation of 3 Relay Orbiters

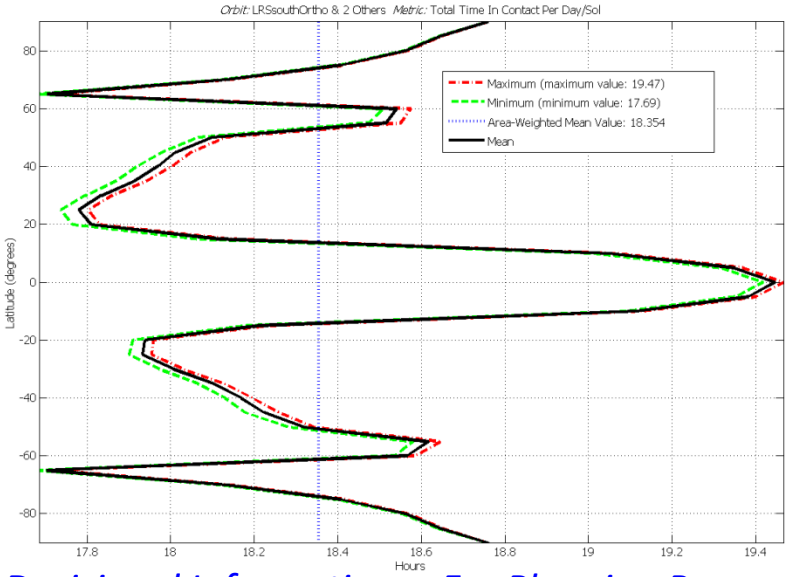
Average Number of Contacts Per Day



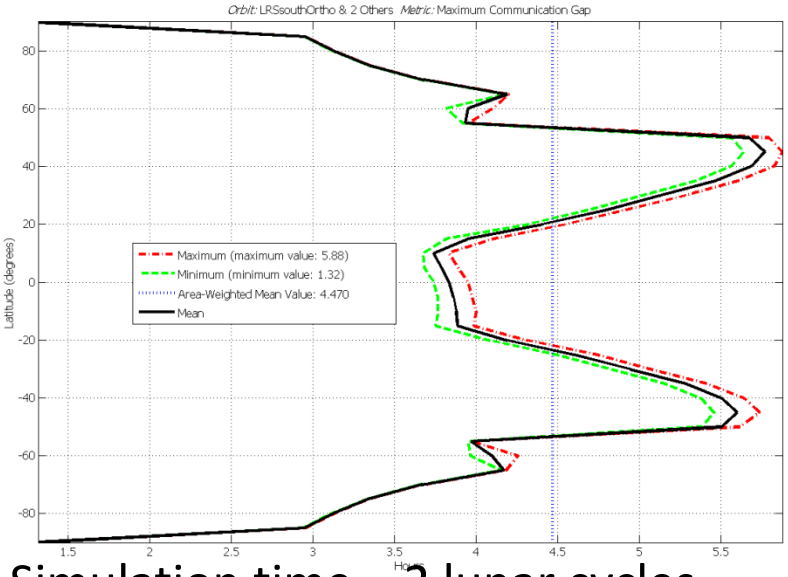
Average Contact Duration (hrs)



Total Contact Time Per Day (hrs)



Max Communication Gap (hrs)



Pre-Decisional Information -- For Planning Purposes Only

Simulation time = 2 lunar cycles

Lunar Network
Advantages of Proposed Lunar Relay Network

- The network can be built up incrementally based on the lunar mission set
  - South Pole, Equator, then North Pole
- Offer good and relatively even coverage at different latitude of the Moon with only three orbiters
  - Long contact durations (5 – 7 hours)
  - Large total contact time per day (17.6 – 19.4 hours)
  - Short gap time (1.4 – 5.8 hours)
- Relatively short range between orbiters and lunar surface assets
  - Maximum range for elliptical orbit = 9.7K km
  - Maximum range for 12-hour circular orbit = 5.9K km
- Low delta-V for station keeping

Lunar Relay Proximity Link
UHF Link Parameters and Data Rates

Relay Orbiter Link Parameters

OrbiterTransmit Power (dBm)	OrbiterAntenna Gain (dBi)	Orbiter Circuit Loss (dB)	Orbiter Noise Figure (dB)	Orbiter Axial Ratio
37.48	4.8	-4.05	3.89	1.5

Surface Vehicle Link Parameters

Lander Transmit-ter Power (dBm)	Lander Antenna Gain (dBi)	Lander Circuit Loss (dB)	Lander Noise Figure (dB)	Lander Axial Ratio
39	0	-1.7	1.4	1

Minimum Datarate bps (Lander to Orbiter)	**Lander Locations**			
Orbiters	Far side Equator	Nearside Equator	North Pole	South Pole
Circular 12-Hour Orbit, Equator	11489	11489	no viewperiod	no viewperiod
Elliptical 12-Hour Orbit, North Pole	4266	4266	5638	92849
Elliptical 12-Hour Orbit, South Pole	4264	4264	92883	5638

Minimum Datarate bps (Orbiter to Lander)	**Lander Locations**			
Orbiters	Far side Equator	Nearside Equator	North Pole	South Pole
Circular 12-Hour Orbit, Equator	38462	38463	no viewperiod	no viewperiod
Elliptical 12-Hour Orbit, North Pole	14283	14281	18875	310831
Elliptical 12-Hour Orbit, South Pole	14275	14275	310946	18876

Lunar – Earth Trunk Link
Use of Ka-Band for High-Rate Data Return

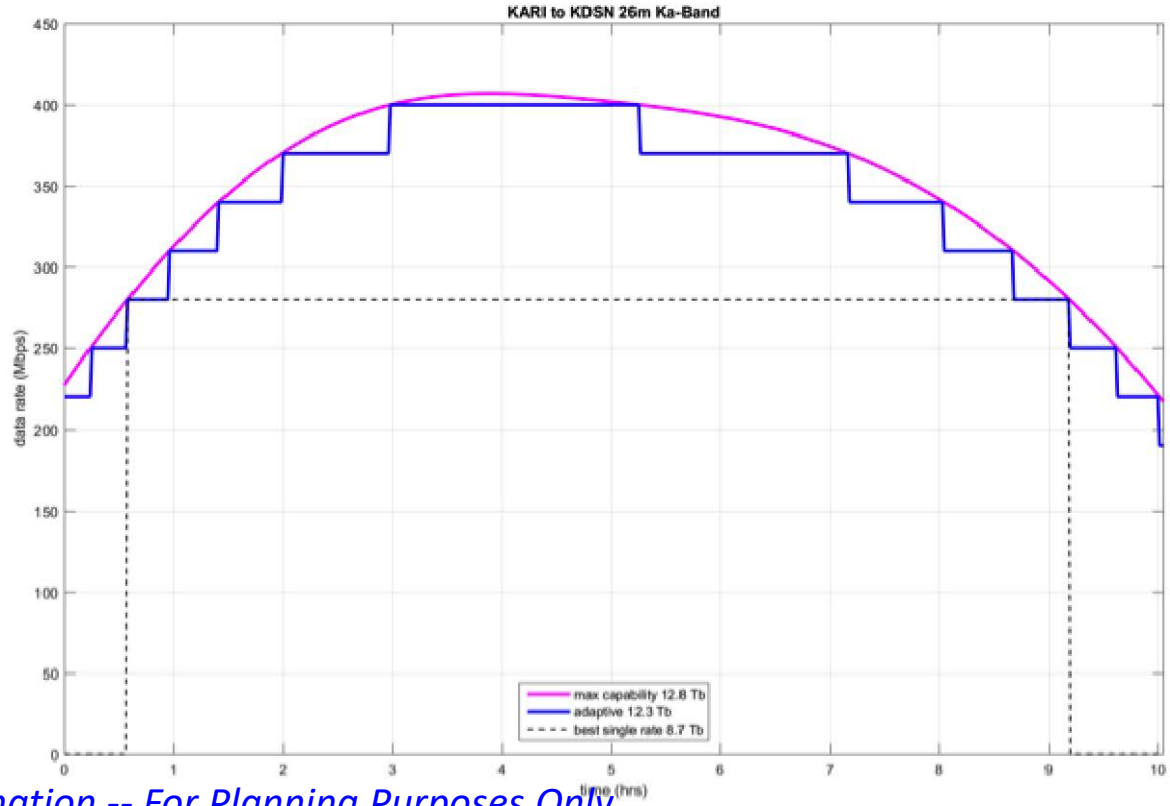
Relay Orbiter Ka-Band Link Parameters

Orbiter Transmitter Power (dBm)	Orbiter Antenna Gain (dBi)	Orbiter Circuit Loss (dB)	Orbiter Axial Ratio	Orbiter Pointing Loss
30	41	-0.5	0.63	-0.98

- Consider both DSN 34-m BWG antenna and KARI's planned 26-m BWG antenna
  - DSN 34-m BWG antenna link parameters
  - KARI's 26-m BWG link parameters are scaled from that of a DSN 34-m antenna, and the weather loss models are employed from the ITU Handbook
- Supportable data rates
  - DSN 34-m BWG: 160 Mbps – 2200 Mbps
  - KARI's 26-m BWG: 30 Mbps – 500 Mbps

Lunar – Earth Trunk Link
Use of Ka-Band for High-Rate Data Return

- Consider Relay Orbiter downlink to KARI's 26-m BWG antenna:
  - **Significant benefit of "Multiple Data Rate Per Pass" strategy and ARQ protocol**. Set of supportable data rates: 10, 40, 70, 100, 130, 160, 190, 220, 250, 280, 310, 340, 370, and 400 Mbps.
  - Total data volume for a 10-hour pass is 20.1 Tb



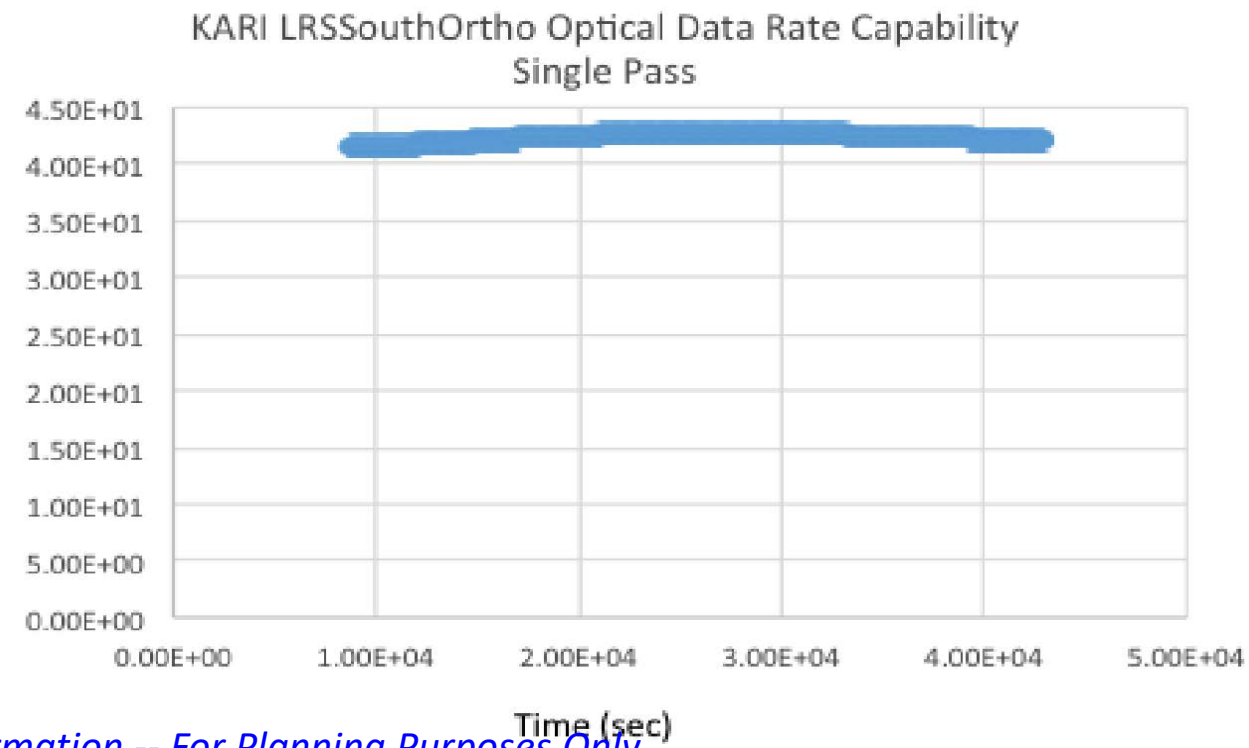
Lunar – Earth Trunk Link
Use of Optical Communication for High-Rate Data Return

- Baseline the flight and ground optical communication systems used on the Lunar Laser Communication Demonstration (LLCD) technology demonstration conducted in 2013

LLCD System Parameters	Values
Spacecraft Laser Transmitter Power (Watts)	0.5
Spacecraft Optical Aperture (cm)	10
Spacecraft Transmitting Modulation	16 PPM (Pulse Position Modulation)
Ground Station Receiving Telescope	4x40 cm (~80 cm equivalent aperture)
Ground Station Photon Detector	Nanowire detector
Operational Constraints	Elevation > 20°,Spacecraft-Earth-Probe (SEP) angle > 5°
Transmit Laser Wavelength (nm)	1550
Spacecraft Pointing Error (µrad)	2.6
Spacecraft Optical Loss (dB)	3.9
Ground Station Telescope Focal Length (m)	10
Ground Station Telescope Optical Loss (dB)	5.4
Ground station Telescope Cleanliness Level	1000
Clear Sky Atmospheric Channel/Turbulence Loss	0.1 dB
Nanowire Detector Efficiency (%)	80
Nanowire Detector Jitter (ns)	20
Downlink Code	Rate ½ SCPPM

Lunar – Earth Trunk Link
Use of Optical Communication for High-Rate Data Return

- Supportable data rate ranges between 41 Mbps and 46 Mbps
- Supportable data rate for a 6-hour pass is shown below. Observations:
  - **Data rate profile is relatively flat, thus no advantage in using multiple data rate changes.**
  - Optical link is sensitive to atmospheric turbulences and weather effects, interleaving and ARQ would help to increase data return and to ensure reliable communication.

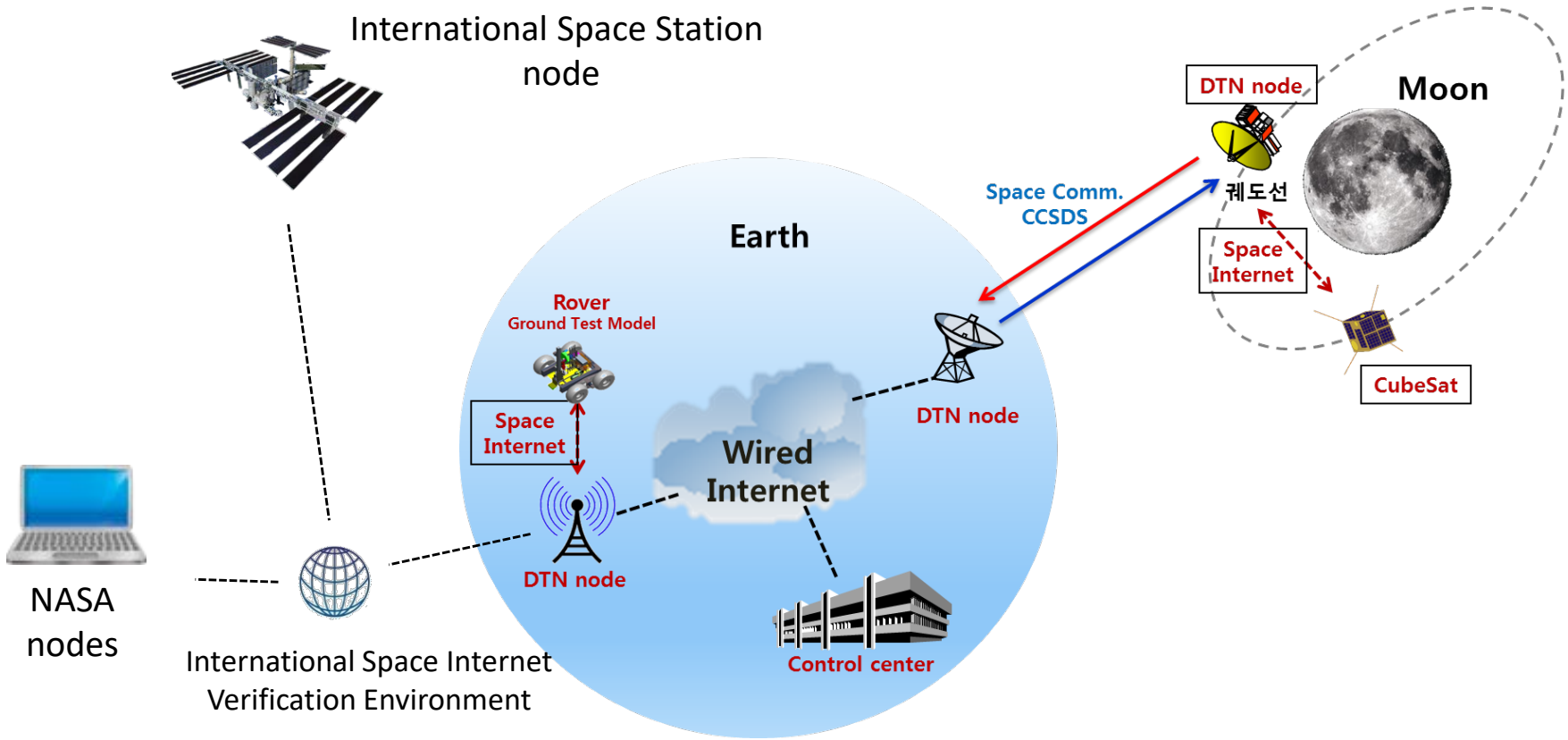


Lunar Space Communications Services
Unify Space Data Link Protocols

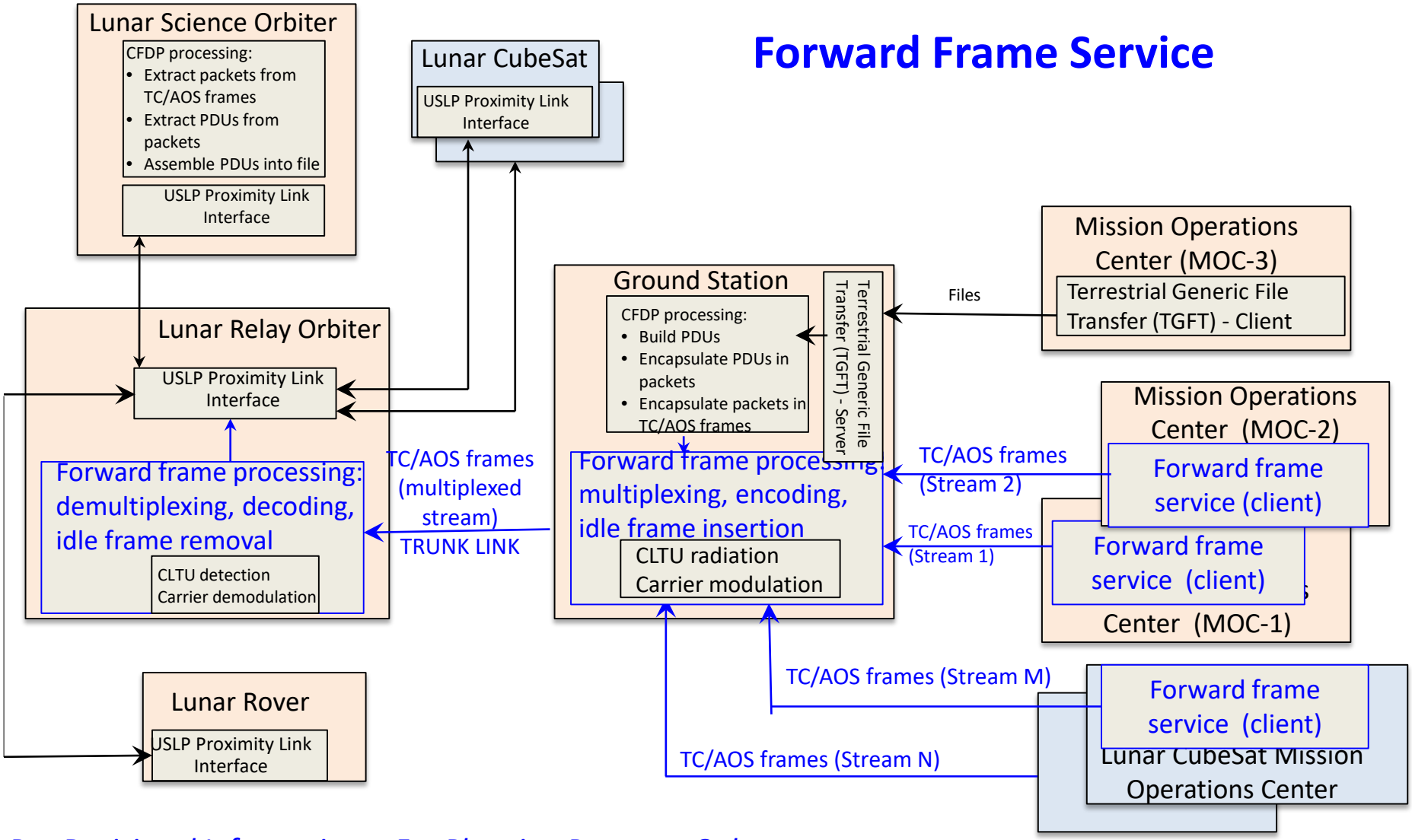
USLP Features	Benefits
Provides a single link protocol used by flight and ground across all manned and robotic space links	• Applicable to large and diverse set of missions from ISS to Cubesats; • Once implemented, reduces future development & testing from 4 to 1 protocol.
Decouples the link framing from the channel coding	a. Using software defined radios, missions may choose to swap in higher performing codes (~3 to 8 dB gain) during development or flight operations. b. Resulting in trade off between using less power (lower output power, smaller antenna or reduced pointing constraints) or opting for higher data rates.
Expands the number of Spacecraft CCSDS must identify	• Existing name space is 75% full. • Expectation is current ID space will run out in the next 5-10 years due to small sat growth and slow attrition.
Allows *direct* data delivery of other protocol data units (PDUs)	a. Currently, CCSDS Space/Encapsulation Packet required to contain other PDUs b. USLP is more efficient using direct insertion requiring no encapsulation of IP Datagrams or DTN bundles

Lunar Space Communications Services
Move To Network Layer Service Involving Multi-nodes

Space Internetworking per Disruption Tolerant Network (DTN)



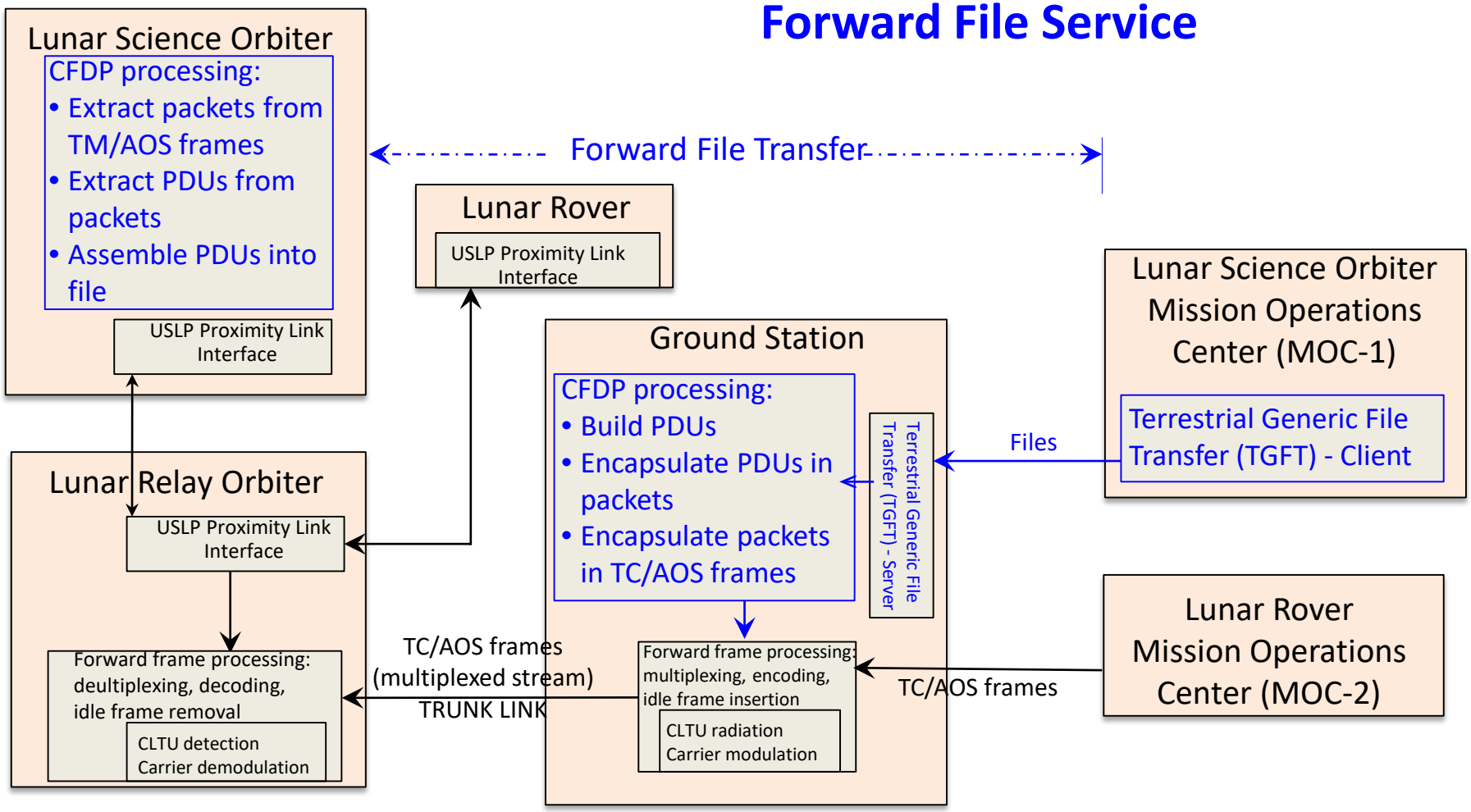
Lunar Space Communications Services -- Simultaneous, Multiple Uplink Streams Over Earth-Lunar Trunk Link --



Pre-Decisional Information -- For Planning Purposes Only

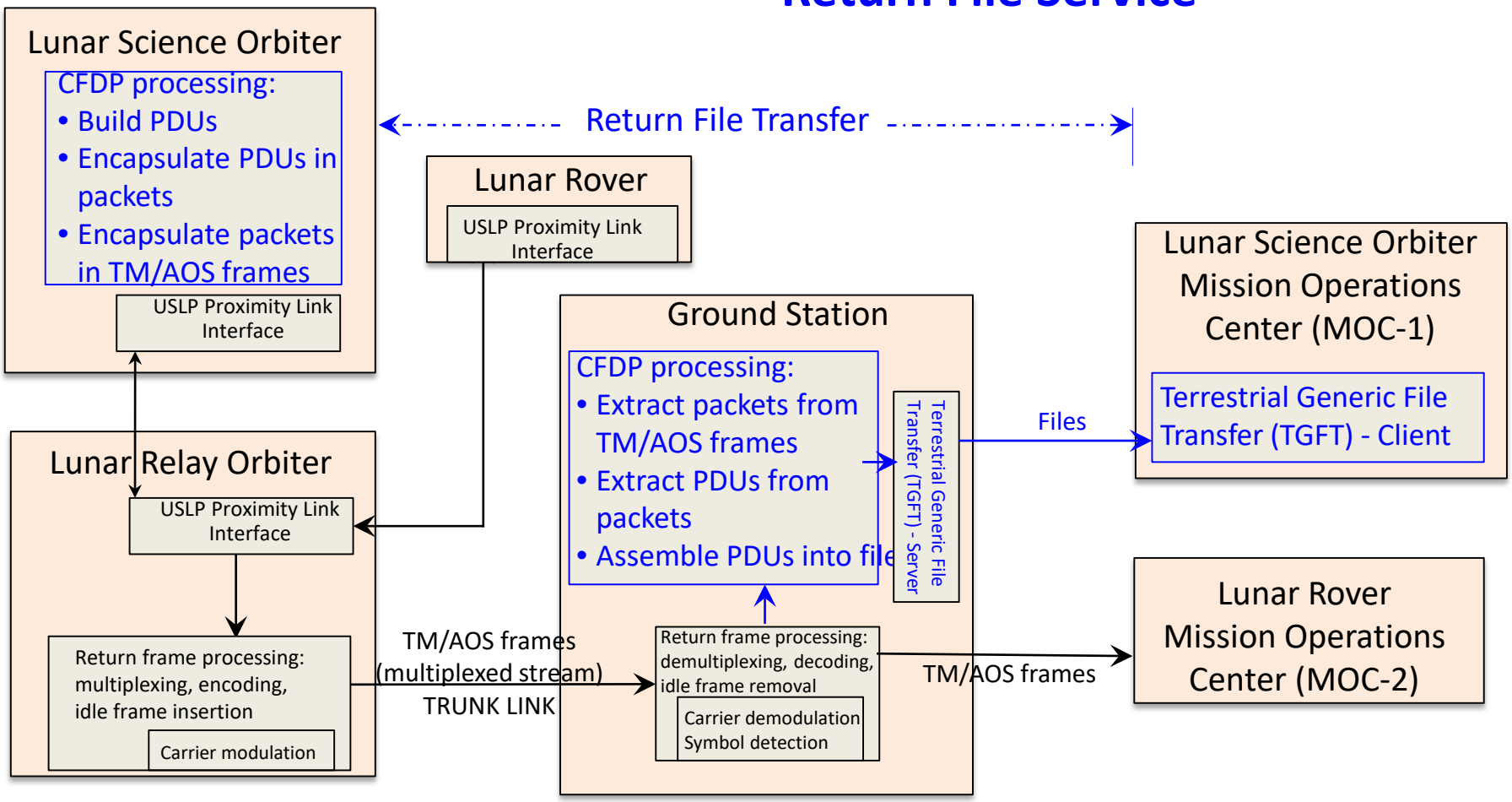
Lunar Space Communications Services
Move To File Layer, End-to-end Service Involving Multi-nodes

Forward File Service



Lunar Space Communications Services
Move To File Layer, End-to-end Service Involving Multi-nodes

Return File Service



The Lunar Space Communications Architecture Conclusion

- The lunar space communications architecture, which would serve as a framework for cross support to the KPLO mission via the communications and navigation capabilities provided by NASA's DSN and the Korea DSN (KDSN), was defined.
  - This architecture may be viewed as a representative architecture for lunar communications during the 2016-2025 timeframe.
- In anticipating the international lunar explorations during the decade of 2026-2035, it is concluded that the 2016-2025 timeframe is a crucial period for the international space agencies to advance the lunar space communications architecture.
  - We have defined an architecture that features a lunar relay satellite constellation, the lunar network, the high-rate links for both Moon-Earth and proximity communications, a new service paradigm, and a set of advanced communication protocols.