NASA LUNAR EXPLORATION – GATEWAY'S POWER AND PROPULSION ELEMENT COMMUNICATIONS LINKS

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Abstract

As a key part of NASA's Artemis program to return to the moon, the Lunar Gateway will provide a platform for staging lunar missions, for gaining experience in operations beyond earth orbit, and for creating sustainable infrastructure. Of specific interest, the Lunar Gateway will provide communications support to landers, orbiters, and surface systems, including in the South Polar Region where direct line of sight (LOS) to Earth is limited or non-existent.

A foundational segment of the Gateway is the Power and Propulsion Element (PPE), which will carry: solar arrays to provide power to the Gateway; electric propulsion to maintain the Gateway in its operational orbit; and communication links between the Earth and Gateway, the Moon and Gateway, and relays from the Moon to the Earth.

PPE Communication Links include an X-band link to Earth for Command, Ranging, and Telemetry (CR&T), which also carries low to medium rate data; a Ka-band Direct to Earth (DTE) link for high rate data transmissions; and a Ka-band Lunar link for high data rate connections to lunar systems.

This paper describes the PPE communication links from a technical perspective. Other Gateway links supported by other modules are outside the scope of this paper.

1 Introduction

Artemis is NASA's program to return humans to the surface of the Moon for the first time since the Apollo missions. It encompasses the Space Launch System (SLS) rocket, the Orion crew capsule, the Human Landing System (HLS), and the Lunar Gateway, in addition to numerous other unmanned landers, rovers, and lunar orbiters.

Further background on the Artemis program and Gateway's role is given in this section, as well as description of PPE's functions and relationship to the Habitation and Logistics Outpost (HALO) and other Gateway elements.

An overview of the Gateway PPE communication links is given in section 2.

Details on the link functions and designs for each of the links are given in Section 3.

1.1 Artemis Program

1.1.1 Early Artemis Missions: Artemis I is the initial flight of SLS and Orion, and is an unmanned mission around the moon. Artemis II is the first manned mission and will last 10-days, proving out the Orion operational systems with crew on board. [1]

Artemis III will be the first manned mission to land on the moon since the Apollo program. The Artemis III mission may be achieved without Gateway, performing rendezvous between Orion and HLS in lunar orbit; alternatively, Artemis III may use Gateway either for crew transfer or just as a communication relay, depending on the resolution of several technical and programmatic questions. Gateway capabilities are being planned to accommodate these uses, if needed.

1.1.2 Gateway Role and Orbit: Beginning with Artemis IV, Gateway will serve as a staging point for manned missions, a platform for science experiments, and a communications relay for both manned and unmanned lunar systems.

Gateway will operate in a near-rectilinear halo orbit (NRHO) around the Earth-Moon L2 libration point. As the Moon orbits the Earth, the angle of the NRHO rotates with it, so that from the Earth-Moon rotating reference frame, the NRHO appears similar to an elliptical orbit, as shown in Fig. 1.

This orbit allows the Gateway to avoid being eclipsed by the Moon, provides continuous line of sight for communication to Earth, has long-duration visibility to the South Polar Region, and good coverage of the far side. [2]

1.2 CMV, HALO, PPE

The PPE has three major functions: Power, Propulsion, and Communications. Power is supplied by roll-out solar arrays which supply up to 65 kW of power [3], and will support power for the station and for the electric propulsion system over the life of the Gateway.

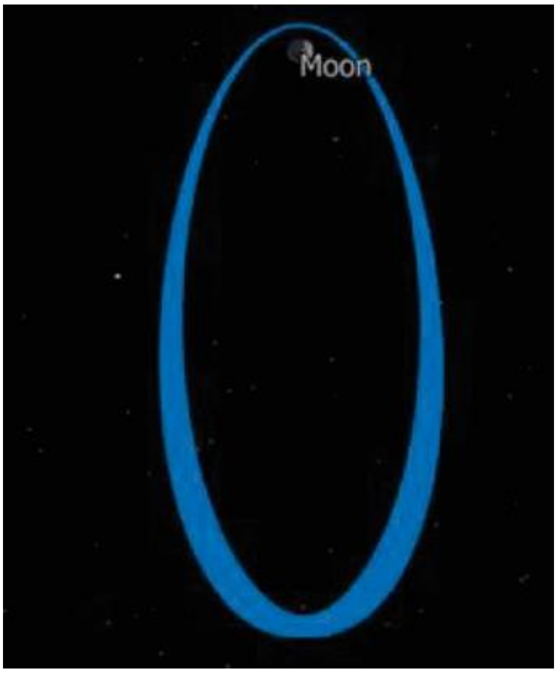

Figure 1. NRHO as viewed from Earth [4]

Propulsion is provided by a combination of three 12 kW electric thrusters, plus four 6.5 kW electric thrusters. The electric propulsion system will raise the co-manifested vehicle (CMV) from its initial orbit to its station in NRHO over an orbit-raising period of approximately one year. The electric thrusters also are responsible for station-keeping in NRHO. In addition there are chemical thrusters to support attitude control.

HALO is the first habitable module of the Gateway. In addition to habitable space and life support systems, HALO has docking ports for Orion and other visiting vehicles, support for rendezvous and docking operations, and accommodation for science experiments and technology demonstrations. HALO carries the Halo Lunar Communication System (HLCS), provided by the European Space Agency (ESA), which supports lunar links at S-band and Ka-band to the HLS and other lunar landers and orbiters.

As part of pre-launch processing, the PPE and HALO will be mated together on the ground and launched in a single flight as a co-manifested vehicle. The CMV is shown in Fig. 2.

1.2.1 Maxar Bus: NASA's approach for Gateway is to procure standard products from major aerospace equipment producers, with modifications specific to Gateway requirements, in order to accelerate development time and gain the benefits of flight-proven hardware and designs. The PPE is produced by Maxar, based on the Maxar 1300 spacecraft bus, which has been used in more than 280 satellites, more than 90 of them currently operating on orbit [5].

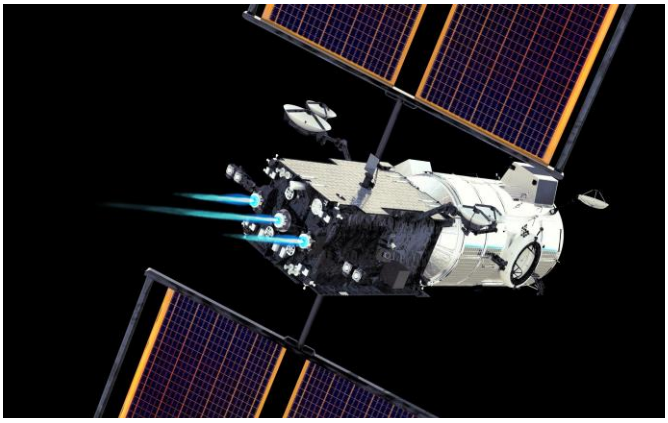

Fig. 2. CMV, showing PPE and HALO

1.3 PPE Communication Links

The PPE communication links perform the major communication tasks of the Gateway: telemetry downlink and command uplink, ranging, high rate data in forward and return links, and medium rate data compatible with smaller ground stations.

The PPE DTE links carry data between the Gateway and Earth, and relay data from the Lunar links, including both the PPE Lunar link and the HLCS links. Fig. 3 shows the CMV link configurations.

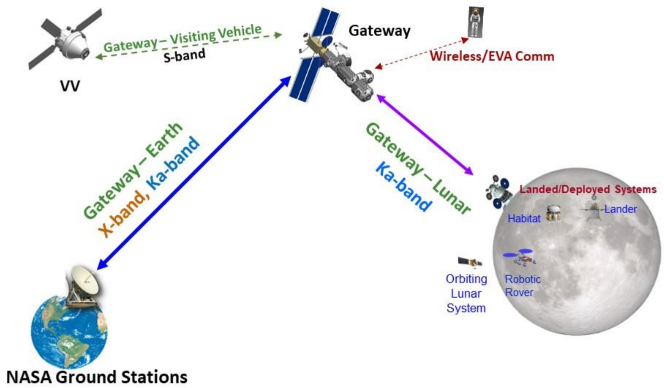

Fig. 3. CMV links to Earth and to the Moon

This paper describes the major communication links supported by the PPE:

- Ka-band DTE Data
- Ka-band Lunar Data
- X-Band DTE Data
- X-Band CR&T

Other communications links provided by Gateway, including the HLCS lunar links, UHF links supporting extra-vehicular activity (EVA), and Wi-Fi supporting intra-vehicular activity (IVA), are outside the scope of this paper. The HALO module also includes an S-Band proximity link to support rendezvous with visiting vehicles, which is supported by antennas on the PPE; but further description is not part of this paper.

2 Communication Link Descriptions

2.1 Ka-Band Direct to Earth link

2.1.1 Function: The PPE is equipped with a Ka-band link to Earth in order to take advantage of the higher data rates available, using the Ka-band equipped ground stations of the Deep Space Network (DSN) [6] and the Near Space Network (NSN) [7].

High rate data needs include data sent from Gateway to Earth and from Earth to Gateway; relay data from lunar systems via PPE Lunar link to Earth; or relay data from HLCS to Earth; and from Earth back to Lunar Systems.

During manned operation, data requirements include astronaut health data, real-time two-way communications, video, and science data. During uncrewed periods, Gateway will continue to run science experiments and relay data periodically; in addition, Gateway will continue to relay data from lunar surface experiments.

Gateway creates opportunities for a range of experiments, which may include optical links as external payload, radio interaction with ion thruster plumes, and others related to the space environment, radio navigation, or communications. To date, two science payloads have been announced: ESA's ERSA and NASA's HERMES [8], which will take measurements of the radiation environment beginning immediately after spacecraft deployment, through orbit raising, and in cislunar space. PPE also carries the Plasma Diagnostic Package (PDP), which will measure the performance of the electric propulsion system on-orbit, and generate large amounts of data. [9]

2.1.2 Frequencies, Data Rates, and Modulation: The PPE Ka-band DTE link operates at 23 GHz in the forward link and 27 GHz in the return link.

The PPE modulation, data rates, and coding conform to the requirements set forth in the International Communication System Interoperability Standards (ICSIS) [10]. The modulation is offset quadrature phase shift keying (OQPSK), which is well-proven in space communication. The lunar link supports low-density parity-check (LDPC) error-correction code rates of 1/2, 2/3, 4/5, 7/8, or uncoded. Forward link coded symbol rates ranging from 5 to 40 Msps, are supported. Return link coded symbol rates range from 25 to 200 Msps.

The typical mode is expected to be 1/2 rate coding, but where link margins support it, higher code rates can be used to increase the data throughput.

All of the PPE links are driven by Software Defined Modems (SDM) of a common design. Further description of the SDM is given in section 2.6.

2.1.3 Antennas and Coverage: The PPE carries two antenna booms, each of which has an X-band and a Ka-band Steerable High Gain Antenna (SHGA) as shown in Figure 4. The antennas share a pallet which is steered by a two axis gimbal, so the X-band and Ka-band SHGAs are pointed in the same direction, within mounting tolerances.

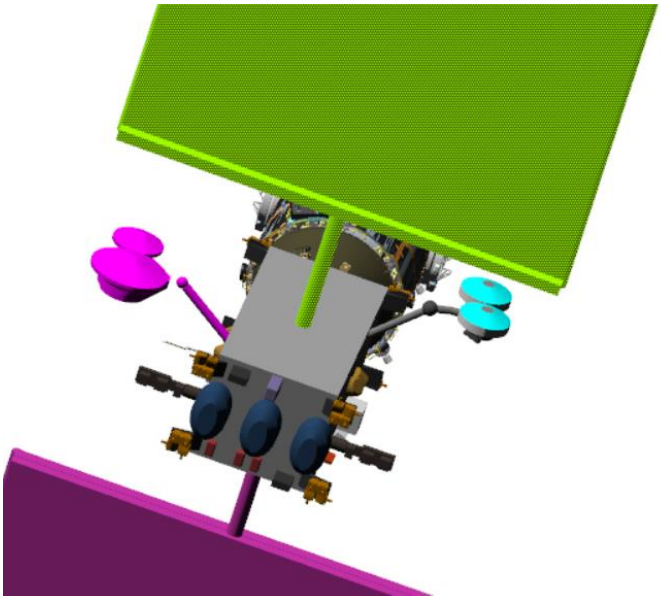

Fig. 4. PPE bus render, showing conceptual SHGA boom configuration

The use of two booms enables line of sight communication between the PPE and Earth nearly continuously, beginning with the initial CMV-only configuration, through the fully built out Gateway configuration with visiting vehicles present. DTE coverage is shown in Figure 5 (a) – (d).

In Fig. 5, the entire sphere around the CMV is shown as triangular tiles mapped into two dimensions. The white tiles are clear sky; the gray tiles represent a blockage caused by the CMV structure. The blue trace between -80 and -110 degrees inclination represents the angle toward Earth, as seen from NRHO. A blockage of the look angle toward Earth by the CMV structure is shown as red in (a), (b), and (c). The combination of both antennas, shown in (d), has no blockage by CMV.

The starboard Ka-band antenna is a 1 m diameter dish [11], and achieves an effective isotropic radiated power (EIRP) greater than 48 dBW and G/T greater than 7 dB/K.

The port antenna has a hybrid function: it can support the lunar link or the DTE link, depending on line of sight conditions and mission demands. To support the lunar link function, it has a slightly larger antenna, with correspondingly higher EIRP and G/T.

The Ka-band DTE link can operate with either 34 m or 18 m ground stations.

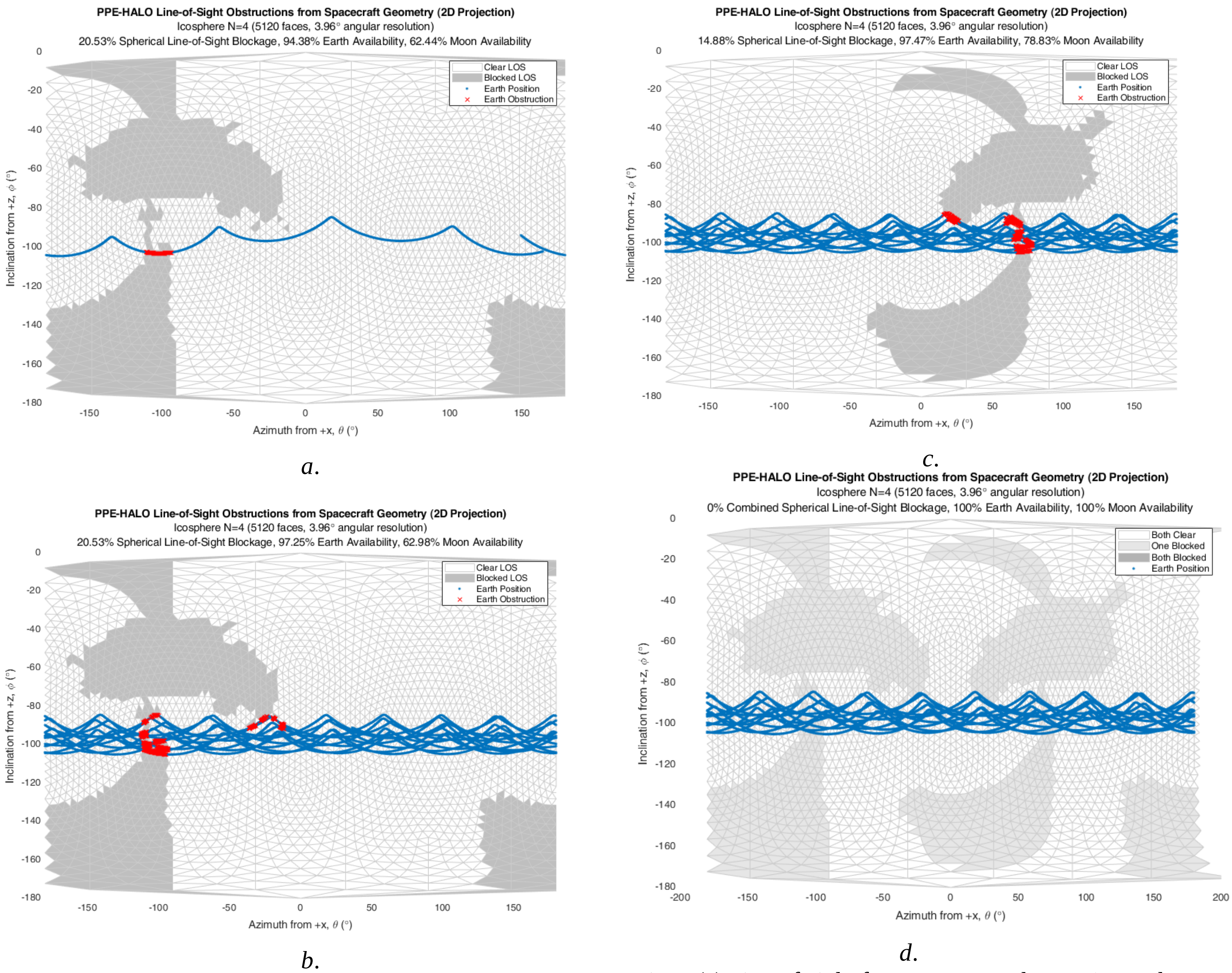

Fig. 5 (a) Line of sight from PPE to Earth over 1 month period, starboard antenna, (b) Line of sight from PPE to Earth over 1 year period, starboard antenna, (c) Line of sight from PPE to Earth over 1 year period, port antenna, (d) Line of sight from PPE to Earth over 1 year period, combined antennas

2.2 Ka-Band Lunar link

2.2.1 Function: The PPE Lunar Link provides communication for lunar systems:

- Surface systems
- Rovers
- Orbiters
- Landers

Lunar systems include manned and unmanned stations, vehicles, and science instruments, and the communication capability supports both Lunar to Gateway links, and Lunar to Earth relays. The lunar link creates the opportunity for real-time remote control of unmanned surface rovers from the manned Gateway with minimal latency.

The PPE Lunar link augments the capability provided by the HLCS lunar links, and enables the Gateway to support up to three lunar users simultaneously. Because the PPE Lunar link frequencies are different from the HLCS frequencies, multiple users can be supported from the same location. Relays between separate lunar locations are also supported.

2.2.2 Frequencies, Data Rates, and Modulation: The PPE Lunar link operates at 23 GHz in the forward link (i.e. transmission from Gateway to the Lunar System), and 27 GHz in the return link (Lunar System to Gateway).

The modulation is OQPSK. The lunar link supports LDPC error-correction code rates of 1/2, 2/3, 4/5, 7/8, or uncoded. Forward link coded symbol rates range from 250 ksps to 1 Msps. Return link coded symbol rates are in the range of 2.5 to 10 Msps.

Typically, the lunar link will operate with 1/2 rate coding, unless higher throughput is needed and link margins support it.

2.2.3 Antennas and Coverage: The port side Ka-band antenna, as previously mentioned, serves both the direct to

Earth link and the lunar link. When it is being used for lunar links, the starboard side antenna is used for the relay to Earth. When the starboard side antenna does not have LOS to Earth, the port side antenna supports the DTE link.

From the NRHO orbit, the Gateway apolune occurs approximately 70,000 km south (in the ecliptic reference) of the lunar South Pole. Over the 6.5 day orbital period, the South Pole is visible from Gateway for all except a period around perilune lasting from 4 to 16 hours. The uncovered periods are due mainly to passing beyond the lunar horizon, but also due to gimbal limits and some blockage, mainly from the solar arrays.

Lunar coverage is shown in Fig. 6. The track of the moon is shown as a series of dots (dark gray), and blockage from the CMV structure is shown as triangular tiles (light gray). The majority of the time is spent near apolune (points shown at the top of the figure), where the only potential blockage is one solar array wing. Options for deflection of the solar array angle, without impacting power generation, are being investigated to further improve coverage availability.

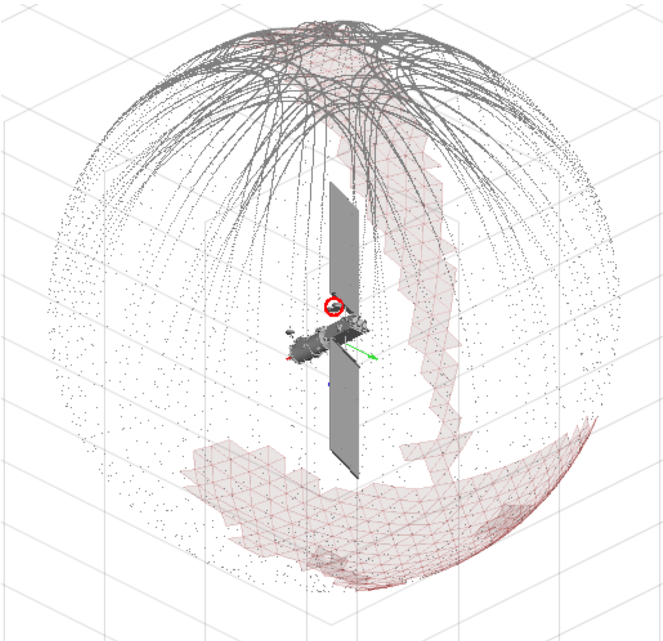

Fig. 6 Visibility to the Moon

2.3 X-Band Direct to Earth link

2.3.1 Function: The X-Band DTE link provides

- High speed data to/from Earth
- Telemetry downlink
- Command uplink
- Ranging (discussed in sec 2.6)

The X-band DTE link is critical as the primary path for Command and Telemetry. Additionally, it provides high speed data links compatible with ground stations which do not yet support Ka-band, or when Ka-band is otherwise unavailable.

During uncrewed periods, PPE can operate autonomously, with periodic, pre-scheduled communication periods for CR&T updates. Communication for science data downloads will also be pre-scheduled.

2.3.2 Frequencies, Data Rates, and Modulation: The X-band DTE link operates at 7 GHz in the forward link (i.e. transmission from Ground to Gateway), and 8 GHz in the return link (Gateway to Ground).

The supported modulations, as defined in [12], are Filtered OQPSK, Filtered binary phase shift keying (BSPK), Pulse Code Modulation/Phase Modulation/Bi-phase-L (PCM/PM/Bi-phase-L), and Pulse Code Modulation/Phase Shift Keying/Phase Modulation (PCM/PSK/PM). The OQPSK and BPSK modes are used primarily for medium to high-speed data and command/telemetry when not ranging; the PCM/PM/Bi-phase-L and PCM/PSK/PM are used for command and telemetry while simultaneously performing ranging, or when required by low link margins (e.g. using the low gain antennas (LGA) from NRHO).

The X-Band DTE link supports LDPC error-correction code rates of 1/2, 2/3, 4/5, 7/8, or uncoded. Forward link coded symbol rates range from as low as 2 ksps up to 10 Msps. Return link coded symbol rates range from 2 ksps to 4 Msps.

2.3.3 Antennas and Coverage: The X-band SHGAs are shown in Fig. 4, and the antenna coverage is shown in Fig. 5.

The X-band DTE link can operate with 34 m, 18 m, or 13 m ground stations.

2.4 X-Band Low Gain Direct to Earth link

2.4.1 Function: To support communications in the early orbit phase, when too much power would violate power flux density (PFD) regulatory limits, and potentially over-drive ground receivers, PPE is equipped with X-band LGAs which can be used in place of the SHGAs. LGAs are mounted on opposing panels of PPE, and together provide nearly 4 pi steradians of coverage. For this reason, they are sometimes referred to (loosely) as omni antennas.

These antennas support high data rates while at low altitude during the orbit raising phase, but most critically support CR&T, at low data rates, at any range from initial orbit to NRHO.

The LGAs are also available to aid in recovery from any off-nominal events resulting in loss of attitude knowledge.

2.4.2 Data Rates, and Modulation:
The modulations and data rates supported are as described in section 2.3.2 for the X-band DTE with SHGA; however, in later stages of orbit raising and after arrival at NRHO, the LGA links will close only with the 34 m ground station and

reduced data rates, e.g. PCM/PM/Bi-phase-L at 128 ksps or lower.

2.5 Ranging

The PPE implements Pseudo-Noise (PN) ranging in accordance with the CCSDS standard 414.1-B-2 [13], and according to the DSN handbook part 214 on ranging [14].

Ranging supports orbit determination by providing a measurement of the distance between the ground station and the PPE. The ranging signal defined in the standard is a pseudo-noise sequence which is transmitted from the ground station to the spacecraft. The PPE receives the uplink ranging signal, and re-transmits it on the downlink non-regeneratively (turn-around mode). Upon receiving the downlink signal, the ground station can determine the light-speed transit time, which is then converted into a range measurement.

Using a chip rate of approximately 2 Mcps, and the T2B ranging code as defined in [13], the predicted probability of signal acquisition is 98%, with an integration time of less than one minute, and 1-meter accuracy. The potential effects of a changing Doppler shift within the integration time are being investigated, along with potential Doppler compensation approaches.

2.6 Software Defined Modems

The PPE SDMs are designed to support any of the PPE links on an as-needed basis. The single design is applicable for all modes and operating bands.

The SDM implements modulation, demodulation from/to samplers and processing LDPC forward error correction encode/decode, in addition to turning around the received PN ranging signal.

2.6.1 SDM specifications: A summary of SDM specifications is given in Table 1.

The SDMs support NASA-required Frame Error Rate ($<10^{-4}$) and Bit Error Rate ($<10^{-7}$), and tolerate a wide range of Doppler offsets and Doppler change rates.

2.6.2 SDM upgradability: The SDM is re-programmable on-orbit via upload from the ground. A flight equivalent unit will be maintained on the ground to check out any new firmware versions prior to uploading to PPE.

2.6.3 SDM Redundancy and Test: The SDMs are connected in a redundancy ring which enables any of the 6 SDMs on PPE to support any of the data links required. This configuration greatly improves reliability compared to a typical 2 for 1 redundancy scheme.

The SDMs also include built-in test modes to aid in troubleshooting any issues.

Table 1. SDM specifications

Item	Specification
Rates (coded symbol rates)	
Transmit	
Filtered OQPSK:	12.2 ksps to 200 Msps
Filtered BPSK:	6.1 ksps to 100 Msps
PCM/PM/Bi-phase-L:	64 ksps to 1024 ksps
PCM/PSK/PM on a subcarrier:	2 ksps to 32 ksps
Receive	
Filtered OQPSK:	24.4 ksps to 40 Msps
Filtered BPSK:	12.2 ksps to 20 Msps
PCM/PM/Bi-phase-L:	32 ksps to 1024 ksps
PCM/PSK/PM on a subcarrier:	2 ksps

2.7 X-band Spectrum

Among the challenges presented by the PPE development is the need to simultaneously meet the spectral mask requirements of the NTIA [15] and the Space Frequency Coordination Group (SFCG) [16] for the X-band transmission containing both CR&T and ranging signals. The plot in Fig.7 shows an example transmitter spectrum for unfiltered bi-phase-L combined with the turnaround ranging signal. In addition, spectrum is also shown for the turnaround ranging signal if it were phase modulated by itself.

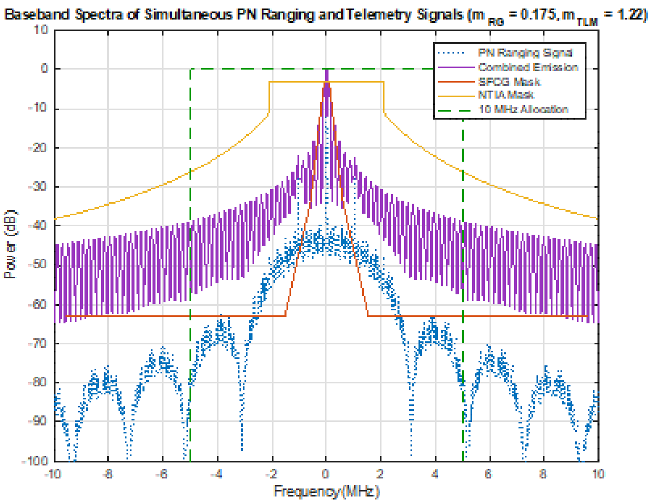

Fig. 7. Spectrum of Bi-phase-L signal with ranging signal

As shown, this combined telemetry and turnaround ranging signal does not comply with the narrow overlaid SFCG spectral mask (red) without filtering. In this case, mask non-compliance results from the telemetry and ranging signals each independently, but then also together. The dashed ranging-only spectrum illustrates its inherent conflict with a telemetry-only based spectral mask definition when the telemetry symbol rate is much lower than the ranging chip rate. Note that PPE is designed to a single, fixed turnaround PN ranging chip rate. It is also readily apparent that the slow sinc-shaped sidelobe amplitude decay of unfiltered phase modulation mode does not meet SFCG's symbol-rate based mask, even with SFCG's less strict low rate mask.

One technical approach to address this issue would be to employ additional filtering for the transmission, however this becomes very challenging when trying to maintain good signal integrity for both the telemetry and ranging signals. The diagram below (Figure 8) presents some context for this challenge.

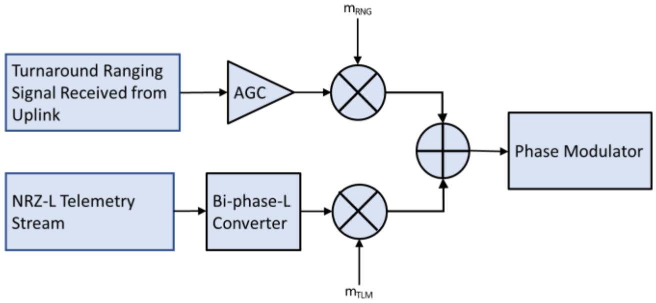

Fig. 8. Block diagram of a generic simultaneous turnaround ranging and bi-phase-L telemetry modulator design

If additional filtering is applied after the phase modulator, spectrum can be well-controlled, but filtering for both the telemetry and ranging is then the same. In lower symbol rate cases that means main components of the fixed-rate ranging signal would be filtered out and cause performance degradation. To avoid this, one could attempt to filter the telemetry signal by itself, doing so prior to combining with the ranging signal and phase modulation. However, filtering prior to the phase modulator does not provide predictable control of the output spectrum since phase modulation is a nonlinear operation. Development of a filtering approach to comply with this mask, without causing excessive degradation to either the telemetry or ranging signals is an ongoing effort but may require certain regulations to be re-evaluated.

3 Summary

3.1 Program Plans

The CMV is planned to be launched in late 2024. Using electric propulsion, PPE will steadily raise the CMV orbit over a period of months, finally achieving NRHO insertion approximately one year later. Under current program plans, the Artemis III mission will be complete shortly after the CMV launch; CMV will be on station to support Artemis IV. However, recognizing that schedules change, provision is being made to enable PPE to operate as a communications relay even before arriving in NRHO, should the need arise.

CMV will then begin its service life as the basis of the Gateway, performing science experiments on-board and relaying science data from lunar systems. Gateway will support manned and unmanned lunar missions over a planned 15 year life.

3.2 Upgradeability

Over the fifteen year life of the Gateway, numerous technology improvements and innovations are to be expected. Because the PPE communications system is based on SDMs, future modifications and upgrades can be made. Potential enhancements include new modulation or coding schemes, improved orbiter tracking techniques, ranging enhancements, and greater integration into NASA's LunaNet architecture for lunar communications inter-networking. [17]

3.3 Future Orbits

The Gateway's orbit, the Southern NRHO, is ideally suited to support missions to the lunar South Pole region, the initial focus of the Artemis program.

PPE is also capable of changing the Gateway orbit during its planned lifetime. Other possible orbits under consideration for later phases, if desired, are a Northern NRHO, which would have the apolune above the North Pole, a Distant Retrograde Orbit, and others. [2]

4 Conclusion

The PPE communication links, together with the HLCS lunar links, provide robust and effective support for all planned Gateway communications, including manned and unmanned missions, and scientific explorations of the surface and cis-lunar space. In addition, the Gateway communication system is designed with a high degree of flexibility to support not-yet-conceived use scenarios as the lunar environment sees an increase in activity over the 15 year mission life.

Major design decisions regarding antenna size and placement, power, link data rates, antenna pointing/availability, Doppler tolerance, and ranging, have been analysed and completed. Detailed designs of the entire RF communications system are being finalized by Maxar.

Remaining work includes some detailed test planning, confirmation of the X-band spectrum approach, and investigation of enhanced tracking approaches for lunar systems in orbit.

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6 Acronyms/Abbreviations

BPSK: Binary Phase Shift Keying
CR&T: Command, Ranging, and Telemetry
CMV: Co-Manifest Vehicle
DSN: Deep Space Network
DTE: Direct to Earth
EIRP: effective isotropic radiate power
ERSA: European Radiation Sensors Array
ESA: European Space Agency
EVA: extra-vehicular activity
G/T: antenna gain to noise temperature ratio
HALO: Habitation and Logistics Outpost
HERMES: Heliophysics Environmental and Radiation Measurement Experiment Suite
HLCS: HALO Lunar Communication System
HLS: Human Landing System
ICSIS: International Communication System Interoperability Standards
IVA: intra-vehicular activity
LDPC: low density parity check
LGA: Low Gain Antenna
LOS: line of sight
NRHO: Near Rectilinear Halo Orbit
NSN: Near Space Network
NTIA: National Telecommunications and Information Administration
OQPSK: Orthogonal Quadrature Phase Shift Keying
PCM: Pulse Code Modulation
PDP: Plasma Diagnostic Package
PFD: Power Flux Density
PM: Phase Modulation
PN: Pseudo-Noise
PPE: Power and Propulsion Element
PSK: Phase Shift Keying
SDM: Software Defined Modem
SFCG: Space Frequency Coordination Group
SHGA: steerable high gain antenna
SLS: Space Launch System