GATEWAY – A COMMUNICATIONS PLATFORM FOR LUNAR EXPLORATION

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Abstract

As stated by a NASA administrator, "NASA, International Partners, and commercial partner are going forward to the moon. With Artemis, we will be exploring more of the Moon than ever before, and this time we are planning to stay. We will be demonstrating new technologies, capabilities, and business approaches needed for future exploration of Mars." To support the complex, Artemis exploration campaign envisioned, the Gateway program is developing a communication network orbiting the Moon. Gateway will provide relay communication paths and radiometric tracking between crewed and robotic systems on the lunar surface or in cis-lunar space to mission control on the Earth. This paper is a high-level description of Gateway's communication and ranging capabilities, the motivation and use of internationally developed interoperability standards, potential upgrade opportunities, and challenges as Gateway enables technology to support future Mars exploration.

1 Introduction

For Moon and Mars exploration, today's public expects high definition video, not the fuzzy black and white pictures from the Apollo missions. Today's science instruments collect enormous amounts of useful data, and principal investigators want to see the full data set as it is available directly, not retrieve it from a server days later. Astronauts living and working on the International Space Station have relied on video teleconferencing capability to stay in touch with loved ones on Earth, communicate with their physicians and trainers, and need the same capability as they explore beyond Low Earth Orbit. Exploration of the far side of the Moon, with its radio quiet characteristics, is of high scientific interest. Exploration of the lunar polar region is a high priority, both for science and exploration. Earth visibility from these locations is limited or non-existent. With multiple campaigns from several nations and commercial entities, current manual scheduling of each Radio Frequency (RF) link to transfer data between the science instrument and the Principal Investigator becomes extremely cumbersome and limiting.

Gateway is being designed to operate with limited Earth communication when there is no crew on-board, but will support near 24/7 communication with Earth when crew is present, either on board Gateway or via the relay capability to crew ascending or descending to the lunar surface or living on the Moon. While crew/assets are on the Moon's Southern pole for long missions, visibility to the Earth will be limited and the Gateway provides communication coverage to fill in the gap. The Human Landing System is expected to use the Gateway to relay the high-resolution images and science data to the Earth to reduce their burden and provide additional coverage.

A range of data rates are needed for communication with ground and with Lunar missions to support crew communication, imagery, data relay from other systems and modules, on-board storage dumps, and science utilization. Ground station sizes will vary, as NASA and commercial and international partners provide Gateway to/from Earth support. The lunar mission capability is in development, and is mass and power limited, requiring Gateway to provide the more robust end of the link. Unlike typical science missions which require a very low data rate to support commanding, crewed missions require much higher uplink rates with low latency to support synchronized audio with video transfer, family communications, and private medical conferences. Ground station upgrades are needed to support the high rate, high coverage needs for crew.

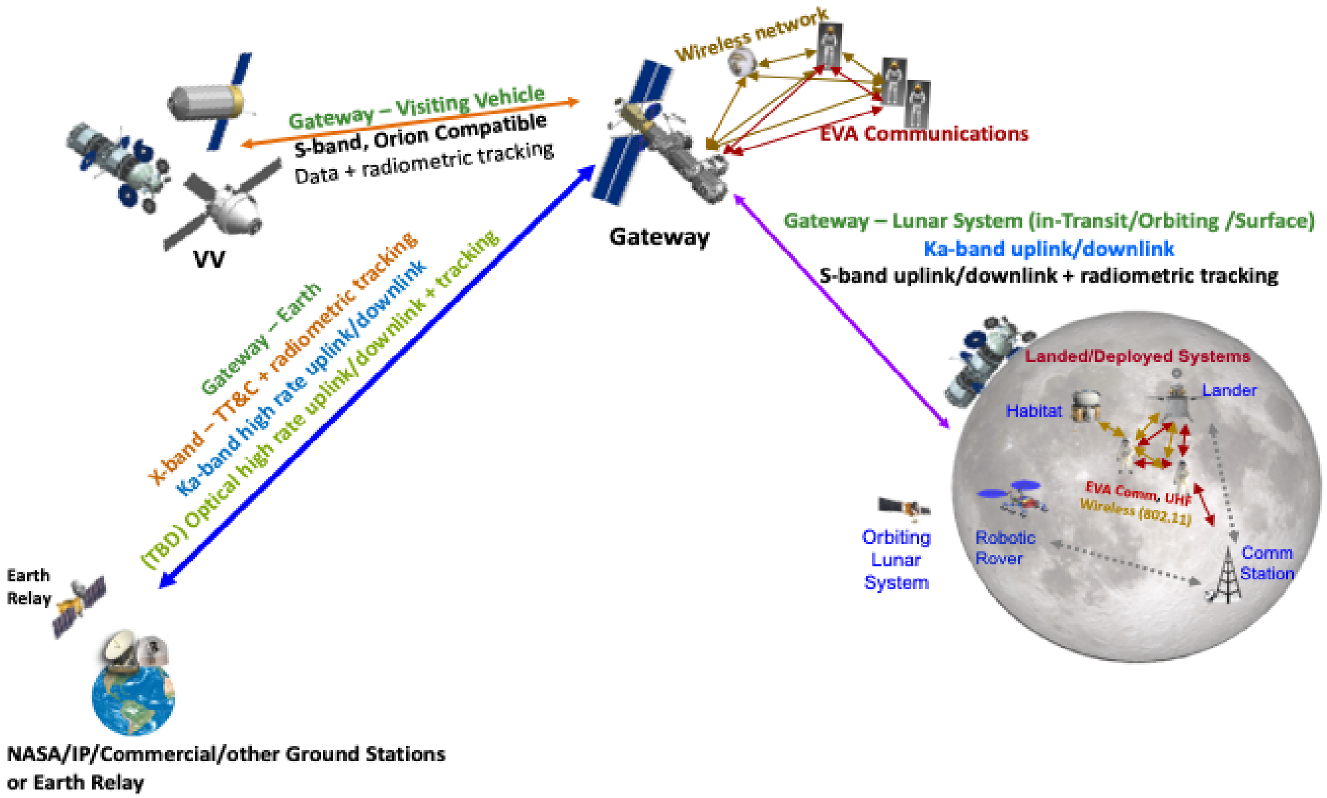

Figure 1. Gateway Communication Architecture

The Gateway architecture includes multiple communication systems (Figure 1). A medium rate X-band and high rate Ka-band direct to/from Earth system will be used for communication and ranging with NASA and international partner ground stations. An S-band and Ka-band lunar system will provide communication and ranging with missions in cis-lunar space or on the lunar surface. A short-range S-band system will be used to communicate with Visiting Vehicles during rendezvous and proximity operations, as well as provide range and range rate measurements to support navigation.

Extra Vehicular Activity (EVA) and Wireless (Wi-Fi) systems are also planned to support external crew activity and local wireless networks on Gateway.

Many challenges and forward work exist for a system of this magnitude and complexity. Gateway must have the flexibility to adapt to the changing Artemis architecture and users, but be mindful of the cost and schedule impacts of changes. And most important, Lunar exploration technology and architecture needs to be “Mars forward”, closing the technical and operational gaps required for Mars and beyond capabilities.

2 Interoperability

Interoperability standards are critical to the success of human exploration and enable use of NASA, international partner, and commercial assets interchangeably, decrease development and procurement costs, and reduce operational and training costs and complexity. It is critical that all human exploration missions are developed using a common interoperability standard. All Gateway RF communication links adhere to the International Communication Systems Interoperability Standard (ICSIS) [1]. The ICSIS is developed by an international body to enable interoperable, cross-supportable, and compatible communications between space vehicles and systems, ground infrastructure, and lunar assets. The ICSIS is consistent with Interagency Operations Advisory Group (IOAG), Space Frequency Coordination Group (SFCG), and Consultative Committee on Space Data Systems (CCSDS) standards and recommendations.

The ICSIS specifies standards for spectrum, modulation, coding, synchronization, ranging, audio, video, network and transport protocols, bundle protocol for Delay Tolerant Networking, and security. Standards and protocols selected are Mars forward and applicable to deep space exploration where practicable. Future revisions will incorporate any additional information or modifications needed for deep space human exploration missions. The protocol stack defined in the ICSIS is shown in Figure 2. Note that this diagram is evolving and not all protocols are implemented in the initial Gateway system. The Advanced Orbiting System (AOS) [2] as the data link layer is the only option selected at this time. Telemetry (TM) and Telecommand (TC) [3] will likely be removed from consideration in the next revision of the ICSIS. Convergence Layer Adapter (CLA) options are also in discussion. Further details on the interoperability approach are in [4].

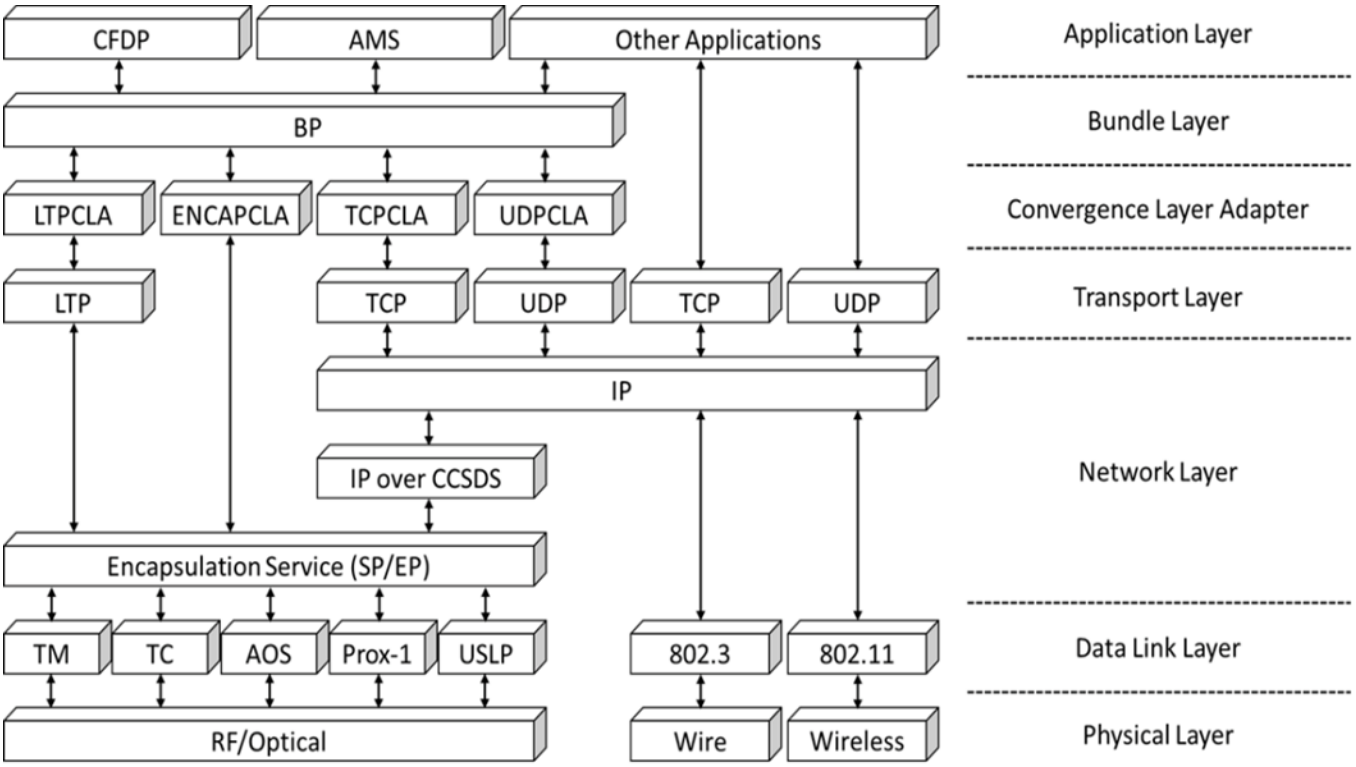

Figure 2. Gateway Protocol Stack Options

3 Mission – Phases and Orbits

Key to the enabling of exploration in the vicinity of the Moon, Gateway will be capable of transferring between various cislunar orbits as well as capable of maintaining itself in the selected Near Rectilinear Halo Orbit (NRHO). Gateway's primary operational orbit is a NRHO of the L2 southern family with a 9:2 Lunar Synodic Resonance, meaning there are 9 orbit revolutions for every 2 lunar months, on average. This NRHO is characterized by an average perilune radius of 3,366 km (~1450 km minimum altitude) over the northern hemisphere, apolune radius of approximately 70,000 km over the southern hemisphere, and average period of 6.56 days. This L2 family NRHO has many advantages for communication, including visibility to the lunar far side, coverage of the lunar south pole, and nearly continuous view of the Earth. It also has non-communication advantages, including lower ΔV and propellant requirements for Orion returning from the NRHO; the ability to avoid eclipses, particularly eclipses by the Earth; and low perilune radius, which is advantageous for lunar surface access [5]. The disadvantages of the selected orbit for Earth and lunar communication include a long range to the lunar south pole at apolune and design complexity to reduce spacecraft blockages to the intended targets. The small relative motion of Gateway at apolune with respect to the lunar south pole may limit navigation measurements for lunar south pole users. Gateway may operate in other orbits, including a Northern L2 and Low Lunar Orbit.

The transit to NRHO from Earth will be approximately one year using the advanced electric propulsion. For missions beyond low Earth orbit, spacecraft size and mass can be dominated by onboard chemical propulsion systems and propellants that may constitute more than 50 percent of spacecraft mass. Since 2012, NASA has been developing a 13 kW Hall thruster electric propulsion string that can serve as the building block for a 50 kW-class solar electric propulsion capability. A high-power, 40 kW class Hall thruster propulsion system provides significant capability and represents, along with flexible blanket solar array technology, a readily scalable technology with a clear path to much higher power systems [6]. The flexibility electric propulsion offers, by its low thrust nature, multiple different trajectory options to transfer from one orbit to another. So far, NASA has developed four Design Reference Missions (DRMs) which include launch vehicle separation to trans lunar injection into NRHO. Assumptions vary between the DRM to trade mass, propellant, time to NRHO, and other factors. Communication analysis is developed for each DRM to capture the link, coverage, and availability information needed to assure that the current communication system design can meet the operational needs of the Gateway.

The primary end-of-mission disposal option is a transfer to a lunar Distance Retrograde Orbit (DRO). The DRO exists because of three body gravitational effects between the Earth and Moon. The assumed target DRO has a radius of approximately 70,000 km and is stable on the order of >100 years. [7].

4 Architecture & System Description

Gateway will have an initial configuration consisting of two core elements: the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). There are multiple communication subsystems within Gateway, allowing support of communication links to and from Earth, Visiting Vehicles, and Lunar Systems, as Figure 1 illustrates. Additionally, the sustaining Gateway architecture will support EVA communications, and will have external and internal Wi-Fi capability. The initial capability is illustrated in Figure 3 as distributed functions among the core PPE and HALO elements.

PPE has the primary Earth connection for Gateway, providing X-band command, telemetry, and ranging; as well as a higher data rate Ka-band link. The mission criticality of the X-band link makes it the most extensive, having both fixed low-gain antennas, as well as two high-gain steerable antennas. X-band low gain antennas provide broad coverage during the transit phase to NRHO and during any contingencies. All the active X-band RF components have backups. Six software defined modems (SDMs) support the three PPE links: X-band with Earth, Ka-band with Earth, and Ka-band with Lunar systems. The X-band uses PN Ranging, described in the next section, to aid Gateway's navigation and mission control tracking. Simultaneous bi-directional operation for the three PPE links is required, which supports the Ka-band Lunar Relay functionality. To conserve mass, the Ka-band Lunar antenna is a shared aperture with the 2nd direct-to-earth (DTE) Ka-band antenna.

Moving larger amounts of data is the purpose of the Ka-band link to Earth. Since there is a wider bandwidth compared to X-band, the Ka-band can move an order of magnitude more data from and to the Gateway, a need for both human and robotic science lunar missions. Although the uplink downlink ratio will not be symmetric, when crewed missions are in operation the higher capacity Ka-band uplink will be important to the crew. But even when the Gateway is uncrewed, the increased Lunar Relay capability that the Ka-band links bring for robotic science missions are significant, and this justifies the new Ka-band uplink capability upgrades for ground systems to support Gateway and other parts of the Artemis program.

Gateway's lunar link capability enables the lunar relay functionality for lunar users without the line-of-sight or resources for a direct-to-earth link of their own. The HALO Lunar Communication System (HLCS), which is provided by the European Space Agency, has capability for two simultaneous links, and the PPE system provides an independent link, thus allowing for three simultaneous lunar users to have relay service via Gateway. These links also provide direct communications between Gateway crew and lunar surface crew as well as other lunar assets.

The HALO element of Gateway has multiple communication subsystems, including lunar S-band and Ka-band from HLCS, Visiting Vehicle S-band, and Wi-Fi. The HLCS S-Band System uses fixed low-gain antennas as well as two high-gain steerable antennas to support low rate communications and ranging. The HLCS Ka-Band system uses the two HLCS high-gain steerable antennas to support the high rate lunar system communications.

Communications with Visiting Vehicles, such as Orion, are provided by communications equipment on HALO, and passive antennas on other Gateway elements to increase coverage. The system operates at S-band and utilizes Space Network type waveforms and supports ranging. This system provides two-way data exchange and ranging to vehicles out to 400 km.

Table 1 lists data rate capacities for some of the links. More details on the PPE Communications subsystem can be found in [8].

Table 1: Initial Gateway Maximum Data Rates

Link	Band	Data Rates (Mbps)*	
		Up	Down
Earth command, telemetry	X	5	2
with Ranging	X	1	1
Earth high-rate data	Ka	20	100
Lunar Systems		Forward	Return
w/HALO	Ka	16	40
w/PPE	Ka	1	10

* User data rates, with ½ rate forward error correction

5 Ranging

The ICSIS has specified the use of pseudo-noise (PN) ranging for the X-band DTE and S-band lunar system links. PN ranging uses a logical combination of range clock and PN codes to measure range and range rate, based on observables in the RF link. For the Gateway DTE links, the ground station transmits the uplink carrier whose phase is modulated by a ranging signal, along with the command signal. The Gateway SDM demodulates the uplink carrier, and the recovered signal is turned around and phase modulated along with the telemetry on the downlink carrier. The ground station uses the demodulated carrier signal to measure the round-trip delay of the ranging signal. For the S-band lunar system link using HLCS, Gateway performs the typical ground station's role of generating the PN ranging code, modulating it on the uplink carrier and demodulating on the downlink carrier, and calculating the two-way time delay. The Lunar System performs the turn-around of the ranging signal functionality. Gateway provides the lunar system's range and range-rate measurements to the Lunar System [9].

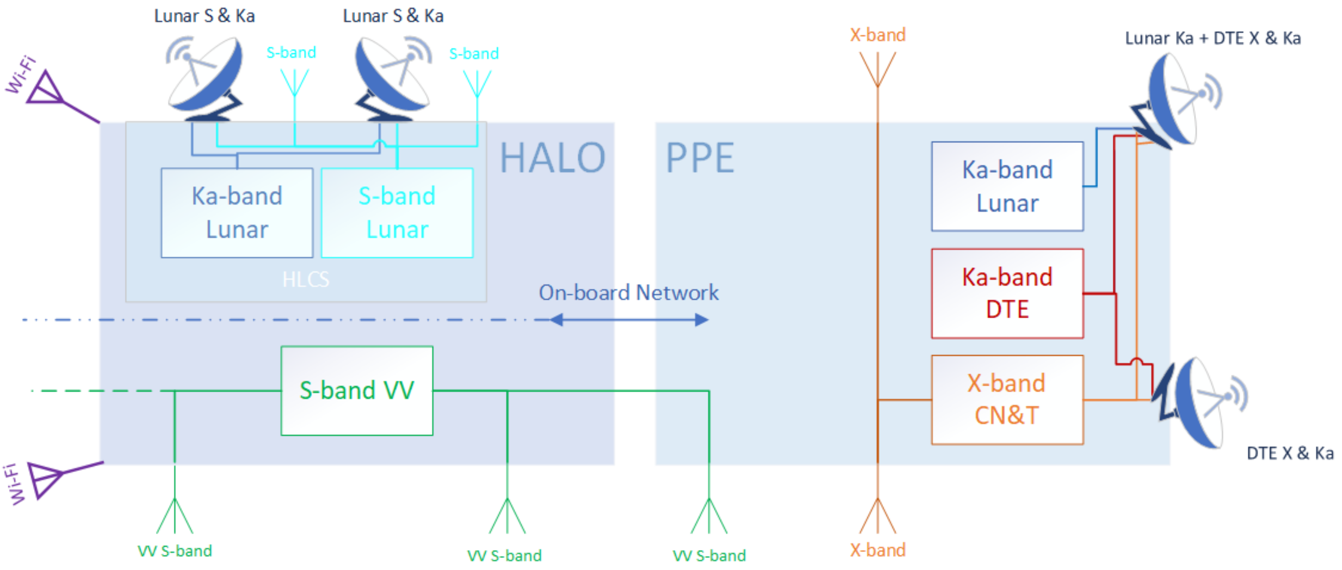

Figure 3: Initial Gateway System

Vehicles docking with Gateway also use radiometric tracking at S-band to determine the range between Gateway and the Visiting Vehicle using the PN spreading approach defined in 450-Space Network Users' Guide (SNUG) [10]. Gateway can operate in the Point A or Point B mode. The system, in Point B mode, generates, modulates, and transmits the range channel data; and it receives and processes the coherent turn-around ranging channel and carrier to obtain the range and range-rate measurements. The system in Point A mode coherently retransmits the received carrier and range channel to support radiometric measurements. When Gateway is in Point B mode, it will provide the range and range-rate measurements to the visiting vehicle.

6 Concept of Operations

The Gateway is a key component of NASA's Artemis Program. As such, Gateway will have a number of communications systems that will enable the Gateway's objectives to serve as an orbiting lunar platform, support research and utilization on Gateway, serve as a waystation for crews and vehicles conducting lunar operations, and provide communication relay services for Lunar Systems.

The Gateway X-band communication system will be activated shortly after launch to provide low rate command, telemetry, and ranging during the transit to the NRHO [5] using the PPE's low-gain antennas. During transit, the PPE's X and Ka-band Steerable High Gain Antennas (HGAs) will be deployed, calibrated, and utilized when necessary for high-rate communications. The HLCS will also be deployed during transit and verified against a ground station emulating a Lunar System. Finally, the HALO's S-band Visiting Vehicle (VV) communication system will be activated and checked against a ground station emulating a VV.

Once in NRHO, the Gateway's HGAs will have excellent visibility to Earth. The PPE X-band system will be utilized for commanding, telemetry, and ranging. The PPE Ka-band system will support a high-rate uplink and downlink with Earth. Functional drivers include "real-time" or "near real-time" mission command/imagery/telemetry, downlink of recorded data/video to support operations, system health status, catastrophic failure analysis, recovery needs, education and public outreach objectives, individual crewmember engagement, crewmember health and medical status, and flight certification of modules. Gateway will utilize NASA ground stations (Deep Space Network (DSN), and Near Space Network (NSN) [11]) as well as augment coverage with other commercial and international partner ground stations as needed to provide the key communications capabilities.

From its vantage point in NRHO, the Gateway will have excellent visibility of the Lunar South Pole for most of the orbit. The Gateway can support at least three simultaneous links and as a result, is able to provide relay communications to and from Earth for Lunar Systems which may not have direct visibility from the lunar surface to Earth or insufficient transmitter power for a direct Earth link.

To support VV and Lunar System operations and Gateway assembly operations, Gateway's S-band communication system will support rendezvous operations. Crewed vehicles such as Orion and the Human Landing System (HLS), as well as supply vehicles such as the logistics module are reliant on this system to dock with Gateway.

7 Key Drivers

Gateway's Radio Frequency communication links must transfer the data required to support a diverse set of science (utilization), spacecraft, and Human Exploration needs for the Lunar Exploration Missions. The data rates required for Gateway to support these missions must consider the transfer volume of non-real time data and real-time data. Examples of non-real time data are generally utilization data, on-board storage dumps, recorded imagery, and file transfers, all of which can be distributed throughout the day when link capacity exists. Real-time data such as live video and audio, commands, and critical telemetry is transferred immediately so the data rate must be greater than the aggregation of this real-time data.

The Gateway-Earth Downlink data rates of up to 100 Mbps support the transfer of data from Gateway and data from Lunar Systems relayed to Earth by Gateway. A significant driver for the data rate capacity on the Ka-Band link to Earth is the amount of utilization data to move from Gateway to users on Earth. A NASA science workshop in 2018 identified a data volume of at least 250 GB to transfer daily [12] and Gateway's design supports more than double this value. The real-time data such as imagery (5-8 Mbps per channel), audio, and crew communications (> 4 Mbps) is also a significant driver for the sizing of the Gateway Downlink when crew are present for Lunar Exploration. Gateway supports relaying multiple real-time HD video channels from Lunar Systems to Earth using the Lunar System-Gateway Ka-Band Link and Gateway-Earth Downlink.

The Earth-Gateway Uplink data rates of up to 20 Mbps support the transfer of data from Earth to Gateway and relayed from Earth to Lunar Systems by Gateway. The significant driver for the size of the Uplink data rates is the real-time data such as HD video and crew communications that are required for crewed missions. Gateway must also support transfer of commands and file transfers on the Earth-Gateway uplink, but these require much lower data rates when compared to the real-time data needs seen during crewed operations.

The Lunar System links on HALO provide two lunar communication links with data rates that support relaying multiple real-time HD video channels, audio, and real-time telemetry from the Lunar Systems to Earth during EVA or remote robotic/rover activities on the Lunar Surface. The Lunar System links on HALO provide data rates to support the relay of HD video from Earth to the Lunar System.

Lunar System links on PPE provide relay capability from Lunar Systems of up to 10 Mbps from the Lunar System and 1 Mbps to the Lunar System. The PPE lunar links are intended to support return of science data from science missions with limited communication capabilities.

8 Upgradeability

With the planned 15-year mission life of Gateway, advancing communication technologies and protocols, and the dynamic nature of international collaboration for Artemis and Moon2Mars, a fixed hardware set of radios is inappropriate. The PPE design has software defined modems to allow for reconfiguration and upgrades in the modulation, coding, or other digital signal processing functionality. The HLCS Ka-band system is also upgradeable. The capability to change or adapt functionality is important for potential anomaly resolution or mitigation as well; to add an interference filter in the receiver, or amplifier pre-compensation to reduce distortion in a downlink.

One currently proposed upgrade is to demonstrate adaptive coding & modulation on the DTE Ka-band link to maximize downlink throughput and reliability, especially for smaller ground stations with less link margin. Throughput or reliability for DTE link passes of several hours would be continuously optimized.

Gateway infrastructure on the ground in the form of an engineering testbed is planned for testing upgrades to the PPE SDMs before changes are made on the flight system. This approach to in-flight changes of software defined radio functionality was demonstrated multiple times on the SCaN Testbed [13, 14, 15].

A user initiative service architecture could be implemented with Gateway, and other lunar relays. Lunar relay, and subsequent lunar network would become more autonomous, reducing the burden on human operators on Earth. This concept has been demonstrated on the SCaN Testbed [16].

9 Challenges and Forward Work

As human exploration of the Moon evolves to include sustained human presence, expanded scientific exploration of multiple lunar locations, far side astronomy, and Mars-forward technology demonstration, Gateway's communication system must also expand. This evolving architecture presents opportunities and challenges to upgrade the existing system safely and effectively with new communication capabilities.

Many spacecraft systems are in development concurrently. Accurately capturing the evolving system requirements in interface requirement definitions (IRD) during the concurrent development presents system engineering challenges. For example, the development of the Human Landing System RF IRD required capturing lower level PPE requirements that were still evolving as the HLS study contracts, which need accurate information on PPE capabilities, were being conducted. Upgrades to the SCaN Ground Stations are needed to support Gateway, while details for PPE's DTE link are being resolved. Coordination by the Gateway system engineering team to manage evolving interfaces is critical.

As the number of nodes in a network expands, network layer routing is the only practical solution to enable end-to-end transfer of information between the human or robotic mission to the principal investigator or user on the ground. This requires a new philosophy for system design and mission operations, and shared operational concepts for the missions under consideration and in development to enable lunar exploration.

As described in the previous section, software defined modems are the primary radios on Gateway, updates to the SDMs can be considered. Upgrades to flight computers are also possible. These upgrades provide the ability to expand communication capabilities and enable additional interoperability as the interface standards evolve and new users are added to the architecture.

Expanding interoperability standards are also needed. Interoperability standards for position, navigation, and timing (PNT) are under consideration. PNT standards are crucial due to the number of missions and agencies involved in joint exploration activities.

An optical communication system installed on Gateway will provide much higher data rates and enhanced ranging accuracy via optimetrics. Adding optical capabilities presents challenges such as: avionics transferring the higher rate efficiently and increased pointing and stability requirements but is necessary and logical for expanded science investigation and crewed Mars exploration.

This is just a short list of the challenges and forward work to achieve the vision for the human exploration campaign.

10 Conclusions

The Gateway communication system is developing with embedded flexibility and adaptability to enable lunar exploration for the next 15+ years. Multiple frequencies, data rates, and code rates enable communication with systems with a range of capabilities from small science systems to large crewed spacecraft. Upgrades will enable additional capability along with technology demonstration opportunities for human Mars exploration. Compatible testbeds for Gateway are in development to support software and firmware development and pre-flight testing. Development testbeds are critical infrastructure for evolving capabilities.

Interoperability will be a key enabler for exploration missions as the architecture evolves, and coordination across all NASA and international partner missions is critical. The interoperability standards must evolve as needed with support from all missions involved in Moon and Mars exploration.

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