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Commercial Data Relay Services in the Cis-Lunar Environment with SSTL's Lunar Pathfinder

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ABSTRACT

Many missions are planned for the lunar environment in the coming decades. Traditionally, all missions would receive telecommands direct-from-Earth and send payload data and telemetry direct-to-Earth. However, missions can benefit from reduced size, weight, power and costs and increased data rates if they forgo space-borne direct-to/from-Earth communications hardware and instead communicate with a nearby cis-lunar data relay orbiter.

Accordingly, SSTL has been working with the European Space Agency under the auspices of the Commercial Lunar Missions Support Services partnership agreement to provide Lunar communications and navigations services. This agreement will see SSTL design, build, test and operate the Lunar Pathfinder spacecraft, a small satellite with a mass of 300 kg that will be placed in an elliptical lunar frozen orbit. Lunar Pathfinder will launch in 2025, and from 2026, provide communications services to lunar missions of all types.

MOTIVATION FOR A LUNAR RELAY SERVICE

Reduced SWaP

The coming decades will see several missions launching into the lunar environment[1], including research space stations[2], missions from universities (e.g. LuSEE-Night)[3], and commercial landers[4] carrying rovers[5] and other payloads (e.g. Firefly Blue Ghost[6]). Traditionally, such missions would receive telecommands (TC) direct-from-Earth (DFE) and send payload data and telemetry (TM) direct-to-Earth (DTE). This obliges these missions to fly dedicated, powerful telecommunications hardware, ultimately resulting in smaller, less performant payloads for spacecraft with given volume, power and mass constraints, thus detracting from the primary mission objectives.

Data relay services can serve an important function for such missions; consider the Friis transmission equation:

$$\frac{P_R}{N_0} = \frac{P_T G_T G_R}{L_{FSPL} L_{channel} k_b T_{sys}} \tag{1}$$

where P_R/N_0 is the signal-to-noise power density at the output of the receive antenna, P_T is the power provided to the input port of the transmit antenna, G_T is the gain of the transmit antenna, G_R is the gain of the receive antenna, $L_{channel}$ is a term to capture further generic losses in the transmission channel (due to atmospheric losses, etc.), k_b is Boltzmann's constant, T_{sys} is the system noise temperature of the receiving system and L_{FSPL} is the free-space path loss, proportional to the square of the slant range:

$$L_{FSPL} = \left(\frac{4\pi R}{\lambda}\right)^2 \tag{2}$$

where R is the slant range between the transmitter and the receiver and λ is the wavelength of the RF carrier.

By communicating with a data relay orbiter in the cis-lunar region rather than directly with Earth, lunar missions can benefit from a slant range reduced by an order of magnitude, saving approximately 20 dB of link margin. Furthermore, channel losses due to transmission through Earth's atmosphere are no longer a consideration for the lunar link budgets. The consequence is that for a given P_R/N_0 and corresponding data rate, lunar missions using data relays can fly less performant telecommunications hardware, saving size, weight and power (SWaP). This means smaller, cheaper spacecraft can be flown, or alternatively leaves more SWaP available for the payload equipment. Practically speaking, TTC / payload downlink antennas can be smaller (reduced G_T or G_R) and / or less complex, and amplifiers can operate at smaller output powers (reduced P_T), drawing and dissipating less power, potentially simplifying power and thermal subsystem designs.

Improved access to ground networks

Another issue with DFE/DTE communications is that as more lunar and deep space missions are launched, the ground networks will become busier and more expensive to access. Already DFE/DTE networks are routinely oversubscribed[7], with significant effort undertaken by agencies and standards bodies in the last decades to identify novel methods to increase access to networks[8]. Issues are likely to be exacerbated as more missions are launched, each with increasing data volume demands.

The consequence of oversubscription is increased operational costs for the user to access the network, and a lengthy and labour-intensive scheduling process for new users. Usage of a data relay satellite reduces the overall number of missions accessing the DFE/DTE networks, alleviating the burden, and thus providing relay customers with cheaper and more timely access to ground stations.

Enabler for far side and polar missions

Data relay satellites also make it possible for customers to conduct missions on the far side of the Moon. Without access to data relay satellites, these missions are obliged to land in polar regions, where extremely low elevation angles can lead to DFE/DTE links being obstructed by local topography. For lander missions that target polar regions, use of a data relay satellite allows communications irrespective of the local topography.

SSTL LUNAR – A DEDICATED TELCO

ESA and NASA support

ESA identified in 2018 that “sustainable” and “affordable” data relay services could be provided by a commercial service provider[9] and in 2019, SSTL signed a collaboration agreement with ESA for Commercial Lunar Mission Support Services (CLMSS)[10]. This agreement covers development of a space segment Lunar Pathfinder by SSTL which commenced in 2020[11].

In 2021, ESA signed as the anchor customer for services from Lunar Pathfinder[12], and purchased additional lunar communications relay services from SSTL in 2023[13]. In 2022, ESA and NASA signed a memorandum of understanding[14] regarding Lunar Pathfinder whereby NASA gain access to the ESA-purchased communication relay services in exchange for NASA launching Lunar Pathfinder and delivering it to orbit through its Commercial Lunar Payload Services (CLPS) programme.

Through the CLPS CS-3 task order placed in 2023, NASA selected Firefly Aerospace to transport Lunar Pathfinder to its required orbit[6]. Lunar Pathfinder will be delivered to its lunar orbit by the Firefly Blue Ghost 2 transfer vehicle, while the Blue Ghost 2 lander will continue to the far side of the Moon, delivering the LuSEE-Night radio telescope and an S-band User Terminal (UT) manufactured by Vulcan Wireless on behalf of NASA. The UT will be used to commission Lunar Pathfinder, and the radio telescope landing on the far side will be dependent on Lunar Pathfinder to relay its science data and TM back to Earth.

Mission Overview and Architecture

SSTL has created “SSTL Lunar”, a telco dedicated to providing commercial data relay services to customers via Lunar Pathfinder. SSTL Lunar and Lunar Pathfinder are wholly SSTL-owned, and the data relay offering is SSTL-operated. Customers of Lunar Pathfinder will be able to select from three separate services, as shown in Table 1:

Table 1: Lunar Pathfinder service offerings

Service	Description
Autonomous	Includes an agreed data volume to be relayed over an agreed timeframe, between the user and the user’s asset via Lunar Pathfinder using automated planning.
Scheduled	As per the Autonomous Service, but with the added possibility for the user to specify the schedule of the communication window.
Emergency	Allows rapid planning and initiation of a Scheduled Service contact within 12 hours of SSTL Lunar receiving an Emergency Service request from the user, subject to ground station availability and visibility of assets.

Further details of the end-to-end service can be found in SSTL’s Lunar Pathfinder Service Guide[15], freely available online for prospective users. SSTL also offer a Lunar Pathfinder Mission Builder application online[16], which can be used by prospective users to perform an initial assessment of the services they can receive through Lunar Pathfinder.

The mission architecture is shown in Figure 1 below, showing the interaction between the Ground Segment (GSEG) and Space Segment (SSEG). Users of the Lunar Pathfinder communications service only require modest ground segment infrastructure to communicate with their asset. Firstly, users connect to SSTL’s Network Operations Centre (NOC) via a Virtual Private Network (VPN); user data is transferred to SSTL’s NOC, nominally 24 hours before the planned uplink. The data are then forwarded to the ground station and uplinked to Lunar Pathfinder, where they are stored in the Lunar Pathfinder data recorder. At the next access, data in the recorder are forwarded to the asset; Lunar Pathfinder establishes a link with the user’s spacecraft via the Proximity-1 protocol, hailing the asset and handshaking prior to commencing data services. Once

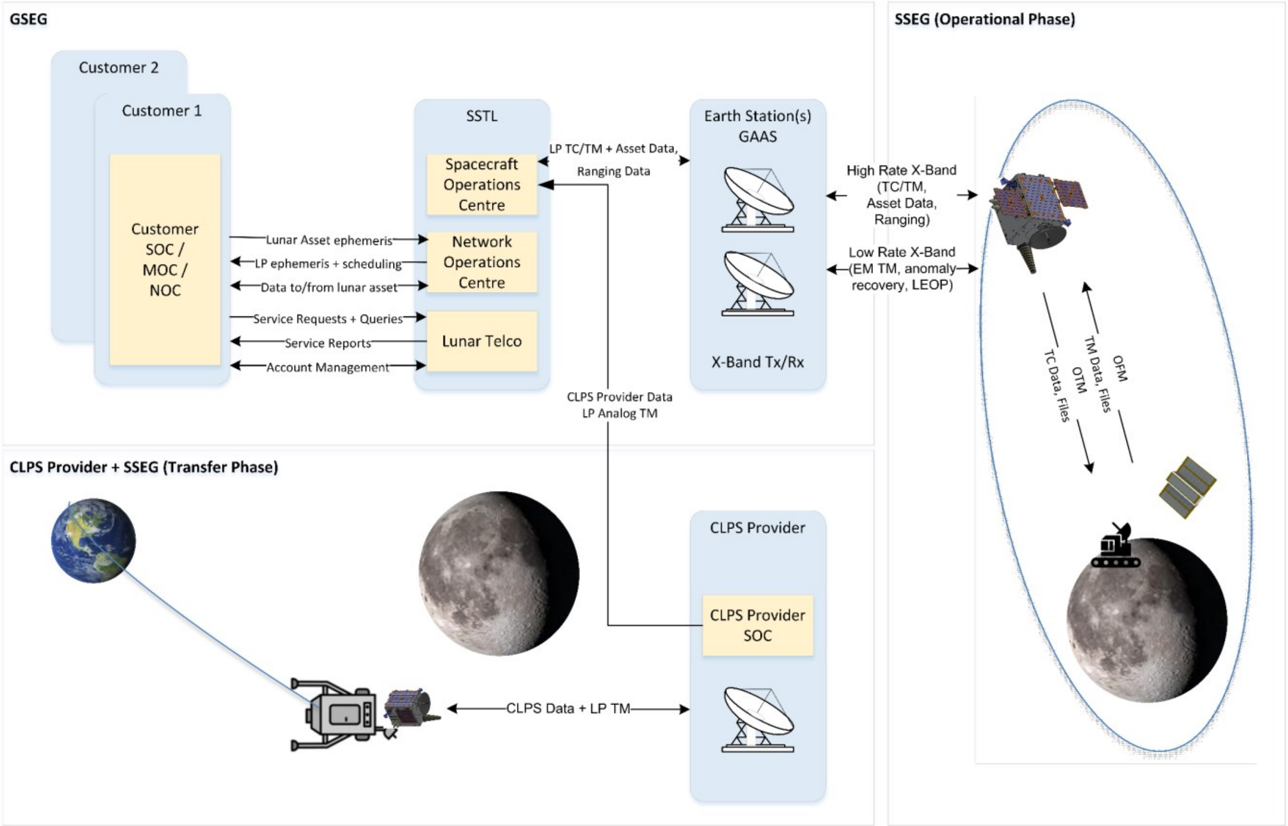

Figure 1: Lunar Pathfinder Mission Architecture

a link has been established, TM and / or payload data can be received simultaneously while transferring uplinked data through usage of duplex communication channels. Data rates can be optimised in line with the link performance through usage of variable symbol rates, as per the features of the data transfer protocol (Proximty-1). Any data received by Lunar Pathfinder are stored in its data recorder, and when commanded, downlinked by Lunar Pathfinder to the ground segment before being transferred to the SSTL NOC and ultimately the user via VPN.

LUNAR PATHFINDER

Overview

Lunar Pathfinder, scheduled for launch in 2025, is a small satellite with an approximate mass of 300 kg. The CLPS CS-3 lander will inject Lunar Pathfinder into a South Pole favouring Elliptical Lunar Frozen Orbit (ELFO), whose orbit parameters have been selected carefully to balance between coverage / contact times with landed assets, and demand on the RF communications subsystem; the values of the orbital parameters are shown in Table 2:

Table 2: Lunar Pathfinder orbital parameters

Orbital parameter	Value
Semi major axis [km]	5740
Periapsis altitude [km]	673
Apoapsis [km]	7331
Eccentricity	0.58
Inclination [°]	54.9
Right Ascension of the Ascending Node (RAAN) [°]	0
Argument of pericentre	86.3
Period	~ 10.8 hours

Lunar Pathfinder has the following core functions:

1. Transmission of TC and file data (software updates, configuration files, etc.) to lunar assets via Ultra-High Frequency (UHF) and S-band
2. Reception of TM and payload data from lunar assets via UHF and S-band
3. Storage and transmission of asset data to Earth via X-band

Lunar Pathfinder also contains third-party hosted payloads:

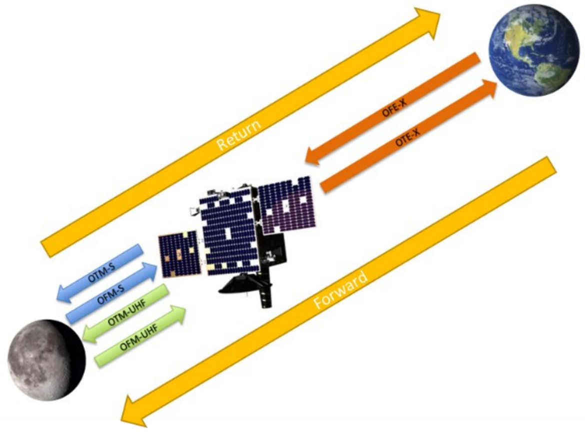

Figure 2: Lunar Pathfinder's Orbiter-From-Moon (OFM), Orbiter-To-Moon (OTM), Orbiter-From-Earth (OFE) and Orbiter-To-Earth (OTE) links in UHF, S-band and X-band

1. NaviMoon, an ESA Global Navigation Satellite System (GNSS) receiver capable of detecting weak signals coming from the Earth GNSS infrastructure (GPS and Galileo)[17]
2. A NASA retro-reflector to demonstrate laser ranging capabilities[17]
3. A radiation monitor to study orbital radiation conditions

The primary mission objectives are realised by an RF payload that is functionally split into two portions, both bridged by On-Board Data Handling (OBDH) and Flight Software (FSW) functions:

1. Earth link payload
2. Lunar link payload

Earth Link Payload

The Earth link payload operates in X-band and its purpose is to facilitate data transfer between Earth and Lunar Pathfinder, and to facilitate two-way transparent ranging for the purposes of orbit determination.

The heart of the Earth link payload is two externally-procured Earth Link Transponders (ELTs) connected to SSTL-manufactured Low Gain Antennas (LGAs), High Gain Antennas (HGAs) and High Power Amplifiers (HPAs), as well as other ancillaries (e.g. switches, filters, etc.). The SSTL hardware all claim heritage from various SSTL developments or LEO missions, with modifications and delta-qualifications undertaken to demonstrate their suitability for usage on Lunar Pathfinder.

Figure 3 shows the Earth link payload architecture. Four LGAs are used to enable wide-coverage, robust communications links; pairs of LGAs are connected to hot-redundant Rx chains. The Tx chains are cold-redundant, with the outputs of the amplifier modules attached to switch matrices that permit SSTL to select which HGA or pair of LGAs should be used for the OTE link.

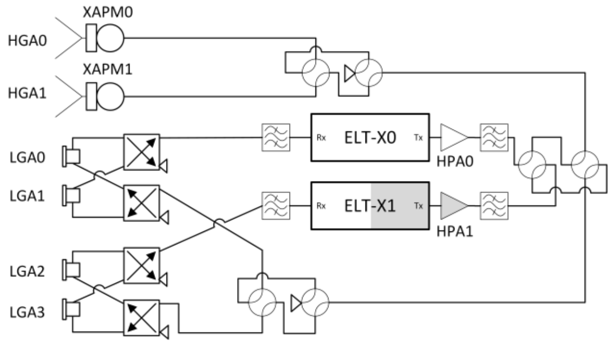

Figure 3: Earth link payload architecture; greyed-out hardware are cold redundant

The HGAs are rectangular horns made of carbon fibre, mounted on antenna pointing mechanisms (APMs). The antenna assembly is near-identical to the assemblies used on SSTL's typical LEO missions[18]. Two HGAs are used to ensure near-constant access to Earth regardless of Lunar Pathfinder's location and orientation. The HGAs are used to downlink payload data and TM on the OTE X-band link at three specific high-speed data rates, as noted in Table 3. Having different high-speed OTE data rates available for selection gives flexibility when selecting ground stations for usage with Lunar Pathfinder and enables usage of less performant ground stations if required.

The LGAs are SSTL-designed septum polarisers, operating in dual Rx / Tx. They are positioned in such a way to maximise coverage and contact time with Earth and provide robust links that are used during the Launch and Early Operations Phase (LEOP), nominally for OFE links, and when the high-speed OTE downlink via the HGAs is not available. Data rates via the LGAs are lower than via HGAs, a consequence of using lower-gain, wider-beamwidth antennas (ref. Table 3).

Table 3: OFE and OTE data rates

Link	ID	Data rate
OFE	TC low	1.8 kb/s
	TC med	28.4 kb/s
OTE	TM med	12.1 kb/s
	TM high 1	1.2 Mb/s
	TM high 2	2.4 Mb/s
	TM high 3	4.8 Mb/s

The HPAs that will be flown on Lunar Pathfinder are based on amplifiers contained within SSTL's latest payload data transmitter, the XTX-800. Modifications are being made to increase the output power, and the transmit filter will be replaced to ensure Lunar Pathfinder self-compatibility and compliance to emission limitations relevant to the lunar environment. The HPAs and the Tx chain of the ELTs work in cold-redundant fashion.

Orbit determination of SSTL's typical LEO spacecraft is achieved through the use of on-board GNSS receivers. In lunar orbit, such a navigation system is not yet available and therefore spacecraft orbit determination must be achieved by RF ranging through on-board ranging transponders, namely the ELTs. To minimise complexity and cost, both on the space and ground segments, a transparent ranging solution compatible with in-force standards[19,20] was baselined.

Lunar Link Payload

The lunar link payload operates in UHF and S-band and its purpose is to facilitate:

1. Reception by Lunar Pathfinder of TM and data transmitted from lunar assets (the OFM link)
2. Transmission of TC or data from Lunar Pathfinder to the lunar assets (the OTM link)

The functions of the lunar link payload are realised through usage of "Lunar Link Transponders" (LLTs), as well as bespoke SSTL-designed Low Noise Amplifier (LNA) modules which are used to drive the overall system noise temperature down. Both are connected to an externally-procured UHF antenna (UANT) and a bespoke SSTL-designed S-band antenna assembly (SANT) via diplexers and a switch matrix to enable switching between prime and redundant LLTs. Figure 7 shows the lunar link payload architecture.

The SANT consists of a carbon-fibre reflector fed by a back-fire helix (Figure 4), mounted on a swashplate-based APM (Figure 5). The entire assembly is designed and manufactured by SSTL, building on heritage developments. The SANT provides high gain for users of the S-band link, with the APM ensuring that the boresight of the antenna stays over the selected region of interest.

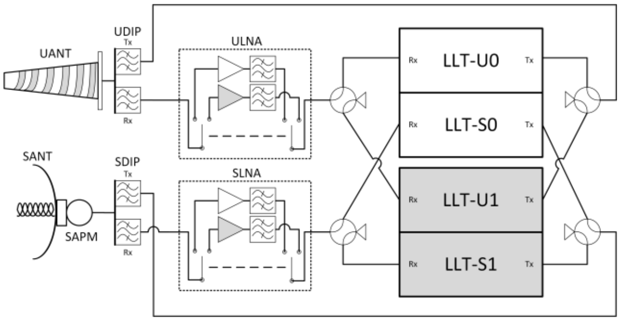

Figure 7: Lunar link payload architecture; greyed-out hardware are cold redundant

The externally-procured UANT is a tall (≈ 700 mm) back-fire helix. The UANT is not steerable, and so the antenna has been designed to strike a balance between gain on

Figure 4: Lunar Pathfinder S-band antenna EQM in SSTL anechoic chamber undergoing RF testing

Figure 5: Lunar Pathfinder S-band antenna APM EQM on the test bench

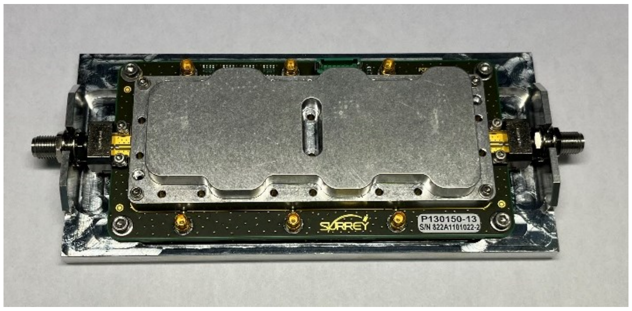

Figure 6: Lunar Pathfinder S-band EQM LNA under assembly at SSTL facilities

boresight and a sufficiently wide beamwidth that ensures that assets in the region of interest can be served.

The LNA modules designed by SSTL (Figure 6) are critical in driving down the system noise temperature of the overall receiver, enhancing the users' return data rates and allowing for relaxed requirements on the LLT, SANT and UANT, minimising unnecessary complexity and cost. The LNA modules are internally redundant as shown in Figure 7, with the ability to be commanded into one of two chains. The LNAs have been designed to have an extremely low noise figure of < 1.5 dB, including source mismatch.

After a detailed market survey and engagement with industry, SSTL awarded the contract to design, manufacture and test the LLTs to QinetiQ. QinetiQ has substantial experience of making Proximity-1 compliant transceivers, having produced Proximity-1 transceivers for Mars Express, Beagle-II, Rosalind Franklin (the ExoMars rover) and the Schiaparelli lander. Two LLTs are being procured and they will operate in cold-redundant fashion, with one LLT capable of serving duplex UHF and S-band links simultaneously. A render of the LLT is shown in Figure 8 below:

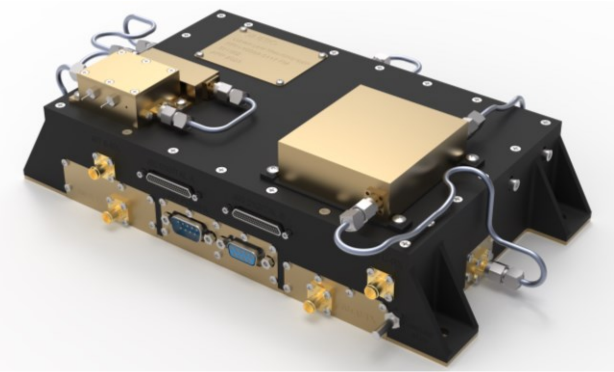

Figure 8: Render of the Lunar Pathfinder LLT, credit: QinetiQ

Proximity-1

A key feature of the lunar link payload is the usage of the Proximity-1 protocol, a bi-directional protocol designed "for the purpose of proximate communications among probes, landers, rovers, orbiting constellations and orbiting relays"[21]. As per the relevant Consultative Committee for Space Data Systems (CCSDS) Green Book[21], Proximity-1 is well-suited for a cis-lunar relay orbiter and its assets:

- It has been designed for communications between spacecraft whose inter-spacecraft distance ranges between ≈ 1 and 100,000 km.
- It strikes an appropriate balance of manual vs. autonomous operations; if links are dropped, the relay can try to re-establish autonomously without ground operator manual intervention.
- Links between the relay and its assets are deterministic and episodic; this allows operators to schedule contacts manually, or autonomously based on the relative geometries of the relay and asset.
- Traffic in the return (OFM) direction will be much greater than in the forward (OTM) direction; the protocol has several features that can be used to accommodate asymmetric data volumes.
- Variable symbol rates are supported, meaning that data throughput can be optimised according to the link conditions; for return (OFM) links, received signal strength indicators on the relay can be used in a closed-loop fashion to command a shift to higher or lower symbol rates
- Supports multiple frequency channels, flexibly.

The protocols span the Data Link Layer[22], Physical Layer[23] and Coding and Synchronisation Sublayer[24], with all three layers being handled by the LLTs, which interface internally with the SSTL-designed OBDH and FSW functions.

When Lunar Pathfinder is ready to set up a Proximity-1 link with an asset, it starts transmitting a carrier-only signal on the forward hailing channel; the receiver sweeps across a range (that covers Doppler and age-related frequency shifts) to acquire the carrier within a defined "Carrier Only Duration". After this duration elapses, Lunar Pathfinder sends "Hail" directives, informing the asset of the link parameters, e.g., which channel to establish a link on, symbol rate, modulation / coding scheme, etc. After the hail directives are sent, Lunar Pathfinder waits for a valid response from the asset, before switching to "data services" mode and receiving (or sending) data. Data transfer is terminated if line of sight is lost (time out), if the link signal-to-noise ratio drops below a pre-defined threshold value (dependent on asset performance and relative geometries), or if the asset reaches the end of its allocated window.

A summary of Lunar Pathfinder's Proximity-1 implementation profile is shown in Table 4 on page 7. An asset needs to fly a Proxmity-1 transceiver that is compatible with Lunar Pathfinder's LLTs. As part of the on-boarding process, new customers of the Lunar Pathfinder data relay service will have discussions with SSTL to ensure compatibility between the asset's transceiver and Lunar Pathfinder's LLTs, and a representative Lunar Pathfinder RF suitcase is likely to be available for on-ground RF compatibility testing with assets.

Table 4: Summary of Proximity-1 features supported by Lunar Pathfinder (see references[22,23,24] for acronyms and definitions)

Data Link Layer	
Qualities of Service	Sequence Controlled (using go-back-*n*, ARQ, reliable), Expedited (unreliable)
Services	Data Transfer Time Transfer (on the forward link only)
Modes	Full Duplex, Simplex Forward / Return
Addressing	Spacecraft Identifier (SCID) Physical Channel ID (PCID) MAP ID (v4 Transfer Frames)
Data Formats	Packets: - CCSDS Space Packets - CCSDS Encapsulation Packets - User-defined data units
Frame Length Data Field (TFDZ)	Return link: Variable up to 65,527 octets Forward link: Fixed at 64 octets for data SDUs. Variable for SPDUs.
Segmentation	Not supported
Session Characteristics	Link and Session Establishment by Hail process (Duplex only) Link and Session Termination by a loss of signal due to a) LP stops transmitting, b) SNR below threshold to maintain link.
Coding and Synchronisation Sublayer	
Coding options	None, Convolutional (7, ½) LDPC (r = ½, k=1024), LDPC (r=⅔, k=4096) (S-band only)
UHF Physical Layer	
Modulation Options	PCM(SP-L)/PM
Frequency (forward)	390 – 405 MHz
Frequency (return)	435 – 450 MHz
S-band Physical Layer	
Modulation Options	PCM(SP-L)/PM, Pre-coded GMSK, BT_s=0.25
Frequency (forward)	2025 – 2110 MHz
Frequency (return)	2200 – 2290 MHz

Lunar Pathfinder's lunar links operate in both S-band and UHF, but the Proximity-1 standards only cover usage of UHF frequencies. This has obliged SSTL, with the support of ESA and NASA colleagues, to propose extensions to the Proximity-1 standards to make it suitable for usage in S-band. Several of the extensions implemented on Lunar Pathfinder are now under consideration for ratification by the CCSDS. The key extensions are:

- Usage of LDPC (r=⅔, k=4096) encoding, yielding improved spectral efficiency (bps/Hz) over that offered by legacy coding schemes with only a negligible increase in threshold E_b/N_0.
- Usage of pre-coded GMSK, BT_s=0.25, yielding vastly improved spectral occupancy for a given symbol rate over PCM(SP-L)/PM.

Further SSTL Proximity-1 innovations include the usage of V4 Transfer Frames (as defined in the CCSDS USLP Blue Book[25]).

As per the Proxmity-1 standards, variable symbol rates are available to be used on Lunar Pathfinder, from as small as 1 kb/s up to 4096 kb/s. On the UHF link, there are no limitations on which symbol rates can be supported, assuming that the link quality is sufficient and access to the modest UHF band allocation has been agreed with regulators. On the S-band link however, higher symbol rates cannot be supported with the PCM(SP-L)/PM modulation scheme; the relationship between occupied bandwidth of a PCM(SP-L)/PM signal and the coded symbol rate is given by the following formula[26]:

$$BW_{\mathrm{PCM(SP-L)/PM}} = 2 \times (26.2m - 5.16)R_{CS} \qquad (3)$$

where BW is the occupied bandwidth (defined as the band of frequencies containing 99% of the total radiated power), m is the modulation index (60° as per Proximity-1 standards[23]) and R_{CS} is the coded symbol rate (defined prior to SP-L encoding).

An example PCM(SP-L)/PM modulated signal with a coded symbol rate of 4096 kb/s yields an occupied bandwidth of ≈ 182 MHz, far exceeding the 85 / 90 MHz S-band allocations in the Lunar environment (see Table 4). Indeed, this drove the usage of pre-coded GMSK BT_s = 0.25 on the Lunar Pathfinder S-band link, whose occupied bandwidth is estimated as per the formula below[27]:

$$BW_{\mathrm{GMSK,BT_s=0.25}} = 0.86 \times R_{CS} \qquad (4)$$

For the same coded symbol rate of 4096 kb/s, this yields an occupied bandwidth of ≈ 3.5 MHz, which is vastly reduced compared to the occupancy when using PCM(SP-L)/PM.

The exact data rates achievable on the lunar links depend on the link quality and the coding scheme employed. Table 5 below shows the relationship between coded symbol rate and data rate. If link margins can support uncoded links, this yields the highest data rate for a given symbol rate (and occupied bandwidth), but this is an unlikely scenario. Most users are anticipated to use some form of coding; users of the S-band link can take advantage of the proposed Proximity-1 extensions and use LDPC (r=⅔, k=4096) to extract higher data rates.

Table 5: OFM and OTM coded symbol rates and data rates depending on utilised coding schemes

Coded symbol rate [kb/s]	Uncoded data rates [kb/s]	Convolutionally coded data rates [kb/s]	LDPC (r=½) data rates [kb/s]	LDPC (r=⅔) data rates (S-band only) [kb/s]
1	1.0	0.5	0.5	0.7
2	2.0	1.0	1.0	1.3
4	4.0	2.0	1.9	2.6
8	8.0	4.0	3.9	5.3
16	16.0	8.0	7.8	10.6
32	32.0	16.0	15.5	21.1
64	64.0	32.0	31.0	42.2
128	128.0	64.0	62.1	84.5
256	256.0	128.0	124.1	168.9
512	512.0	256.0	248.2	337.8
1024	1024.0	512.0	496.5	675.6
2048	2048.0	1024.0	993.0	1351.3
4096	4096.0	2048.0	1985.9	2702.5

CONCLUSIONS

This tehcnical paper has demonstrated that cis-lunar relay satellites have a key role to play in the coming decades as increasing numbers of lunar missions are launched. SSTL is in the vanguard, ready to contribute to the nascent lunar ecosystem via its pioneering Lunar Pathfinder spacecraft which will launch in 2025 and provide data relay services to ESA, NASA and commercial customers. SSTL, with institutional stakeholders and sub-contractors, has already contributed to innovative developments on Proximity-1, helping to shape the future of lunar communications, particularly in S-band. If you, the reader, are interested in securing data relay services via Lunar Pathfinder, please contact SSTL at lunar@sstl.co.uk.

ACKNOWLEDGMENTS

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SSTL further thanks NASA for agreeing to launch Lunar Pathfinder and deliver it to lunar orbit via the CLPS CS-3 task order.

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