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# Lunar Pathfinder – Commercial data relay satellite enabling the next generation of lunar missions

**A. Ilott[a]*, N. Offord (Phillips)[a], J. Friend[a], B. Schwarz[a], M. Christie[a], D. Binns[b], M. Krynitz[c], Sir M. Sweeting[d]**

[a] *Surrey Satellite Technology Limited (SSTL), Tycho House, 20 Stephenson Road, Surrey Research Park, Guildford, United Kingdom, GU2 7YE,* lunar@sstl.co.uk
[b] *European Space Agency (ESA), European Space Technology Centre, Keplerlaan 1, 2201AZ, Noordwijk, Netherlands*
[c] *Kongsberg Satellite Services (KSAT), Drammensveien 165, Oslo, Norway*
[d] *Surrey Space Centre, BA Building, University of Surrey, Guildford GU2 7XH*
* Corresponding Author

**Abstract**

The dawn of a new era in space exploration beckons. Channelling the ethos of New Space, international endeavours with private industry at the vanguard have set their destination to Earth's closest natural satellite, Luna. The goal – unlock the scientific, commercial, and technological opportunities of the Moon to build the foundations of a sustainable ecosystem. This paradigm shifting vision requires a symmetry in approach – a new way of working. Technological innovation and disruptive business models have catalysed an expanding sphere of commercial lunar activities, looking to establish trade and industry on the next frontier. Surrey Satellite Technology (SSTL) seek to facilitate this lunar renaissance with their commercial data-relay service, provided through Lunar Pathfinder.

Lunar Pathfinder is SSTL's single spacecraft in lunar orbit, offering communication services to any lunar asset (surface or orbiter). Due to launch Q4 2025/Q1 2026, the spacecraft will be fully operational in 2026 with a service duration of 8 years. This programme is done in collaboration with the European Space Agency (ESA), under the Commercial Lunar Mission Support Services (CLMSS) initiative and serves both as a technical demonstrator for lunar communication services from a small satellite, and a proof of concept for the commercialization of a shared infrastructure.

This service will address the challenges faced by lunar missions solely using direct-to-Earth (DTE) communications for transmitting data back to their ground stations. DTE requires a direct line of sight, which is only constantly available on the near side of the Moon. Lunar Pathfinder's orbit allows it to relay communications for those missions on the far-side and polar regions, unlocking a plethora of exploration opportunities. The goal of the Lunar Pathfinder service is not to replace DTE, but to augment it, maximising the value delivered to the end-user. SSTL are working in collaboration with ground station provider Kongsberg Satellite Services (KSAT), to offer a seamless service package, combining the strengths of DTE and data-relay communications.

Lunar Pathfinder demonstrates how small satellites can provide innovative commercial services, and enable the ability for lunar assets to carry out data intensive missions. This paper will detail the motivations and market opportunities for a lunar communications service as well as the programmatic framework which facilitated such a service. Additionally, details of the spacecraft and hosted payloads on-board will be discussed, as well as the challenges faced in establishing a network for lunar communications.

**Keywords:** exploration, lunar economy, lunar services, lunar operations, data-relay, Ground Station as a Service (GSaaS)

**Acronyms/Abbreviations**

| | |
|---|---|
| CLPS | Commercial Lunar Payload Services |
| DTE | Direct to Earth |
| DSN | Deep Space Network |
| ELFO | Elliptical Lunar Frozen Orbit |
| ESA | European Space Agency |
| FWD | Forward |
| GNSS | Global Navigation Satellite System |

ISRO Indian Space Research Organisation
ISRU In-Situ Resource Utilization
KSAT Kongsberg Satellite Services
LCNS Lunar Communications and Navigation Service
LRR Laser Retroreflector
PNT Positioning, Navigation and Timing
RTN Return
SSTL Surrey Satellite Technology Ltd

## 1. Introduction

The moon has long captured the imagination of humanity, from ancient mythology to modern scientific exploration. For centuries, it has served as a symbol of our quest to understand the cosmos and our place within it. After the first successful lunar landing in 1969, the moon became a tangible symbol of human achievement, and a source of inspiration and pride for people around the world. Unfortunately, these early successes failed to catalyse the lunar revolution that was once expected. In the decades following Apollo, public interest waned, available funding along with it, and the moon receded into the background of Earth's space exploration efforts.

However, in recent years, there has been a renewed interest in returning to the moon, driven by a variety of scientific, economic, and geopolitical factors. This new era in lunar exploration aims to shift focus away from siloed lunar activities, towards the construction of a sustainable lunar ecosystem. While this vision of an interplanetary economy is truly unprecedented, parallels can be drawn, and lessons learned from our terrestrial history. Critical infrastructure shaped the vector of society's advancement, allowing humanity to enjoy the non-linearity of compound growth that has propelled us to where we are today. In the same way, lunar infrastructure will facilitate an ecosystem that is greater than the sum of its parts.

Using the incumbent lunar communications solutions of today, in certain cases on the Moon, vital communication capabilities are only available intermittently, and in some locations, not available at all. On Earth, this is unthinkable. When envisioning a sustained human presence on the Moon, seamless communications, networking, and connectivity abilities are essential. In contribution to the one of the first nodes in this communications infrastructure, Surrey Satellite Technology (SSTL), in partnership with the European Space Agency (ESA), have developed Lunar Pathfinder – a single satellite providing lunar data relay services. Lunar Pathfinder's communications offerings will liberate users from the burden of implementing a costly and complex independent solution, while providing more robust communications capabilities. This will catalyse growth across a number of nascent lunar markets, heralding the genesis of a thriving lunar economy.

This paper describes Lunar Pathfinder from an end-to-end perspective – presenting the market opportunity for lunar communications, the programmatic framework that supports it, the spacecraft, the service and its operations, while also providing an insight into the downstream operations of a lunar ground station network. The paper begins by explaining the commercial opportunity for lunar services, informed by both internal and external market intelligence. In the section following, the programmatic framework of a lunar exploration partnership between institution and industry is described. The mission is then detailed, including a high-level description of the Lunar Pathfinder system design, its initial service offerings, and the considerations of operating a satellite in a lunar environment. The paper is concluded by describing the challenges of establishing a ground station network for lunar communications.

## 2. The Nascent Lunar Market

### *2.1 Market Drivers*

The samples returned from the Apollo missions seemingly confirmed a long-held scientific believe – the Moon was almost completely baren of any volatile resources [1]. Although trace amounts were found in these studied samples, this was assumed to be the consequence of contamination. While an important part of our cosmological history, and a site of great scientific interest, the consensus was that the Moon offered little for the possibility of human habitation and settlement. Decades after these initial studies, mapping of the lunar surface from the Indian Space Research Organisation's (ISRO) Chandrayaan-1 spacecraft in 2008 provided unequivocal evidence that the Moon was not as dry as once thought, discovering water ice at the poles of the lunar surface [2]. In the missions that soon followed, observations determined that additional deposits of water exist on the Moon at other locations [3,4].

The lunar water discovery effort is still ongoing. NASA's Lunar IceCube, PRIME-1, and Lunar Trailblazer missions are bound for the Moon within the next 2 years. Equipped with more advanced, more sensitive instruments, they will characterize the full potential of the once assumed baren lunar surface. This water has the potential to sustain a more permanent human presence on the Moon, being used for resource utilisation to produce air, drinking water or propellant. Human settlement on the Moon unlocks an opportunity for private companies to contribute to ongoing lunar activities, energizing industry to action in order to capture some of the potential value of the lunar economy.

Since Chandrayaan-1, many barriers to the exploration industry have been lowered. Space technology has experienced improved maturity and falling costs, a more entrepreneurial space industry has emerged supported by public private partnerships, there is an increased investment appetite for the space industry (attracting more private capital), and lunar exploration has become more aligned with geopolitical policy and strategy. The synergies between these factors have re-ignited a global interest in returning to Earth's nearest satellite, unlocking a plethora of scientific and commercial opportunities.

*2.2 Market Opportunity*

These opportunities have resulted in bullish analysis on the outlook of the lunar economy. In their lunar market assessment [5], PwC forecast markets for lunar goods and services to grow to a cumulated $170 billion over up to 2040. Space market analysis firm, Northern Sky Research, published their Moon Market Analysis report [6], estimating that the Moon economy is set to generate over $100 billion between 2021-3031, with over half of these revenues generated commercially. The third addition of Euroconsult's Prospect for Space Exploration report [7] forecasts global governmental space exploration investments to reach $31 billion by 2031. They also state that government investment towards space exploration in 2022 was 59% higher than 10 years ago.

SSTL have been carrying out internal analysis on the anticipated market for lunar communications services since the conception of Lunar Pathfinder years ago. This analysis involves identifying known missions, characterizing the communication needs of these potential customers based upon their type, and synthesizing the data through a Monte-Carlo statistical analysis to account for uncertainties in the market. The output of such analysis is a lunar traffic model to predict the demand for communication and navigation services over the next 20 years. Examining the results, a few trends can be identified:

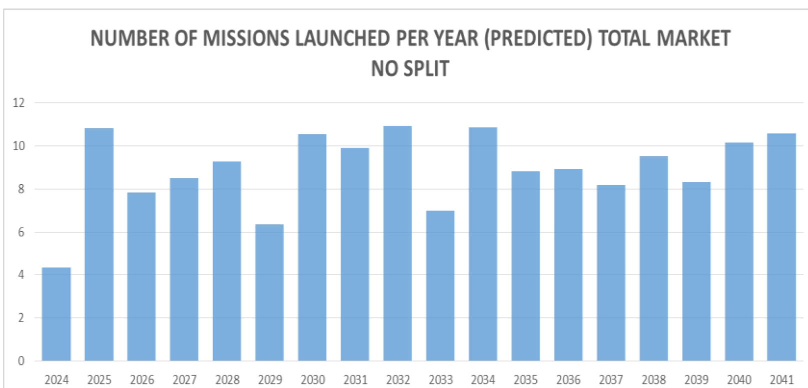


**Figure 2-1: Mean number of missions launched per year**

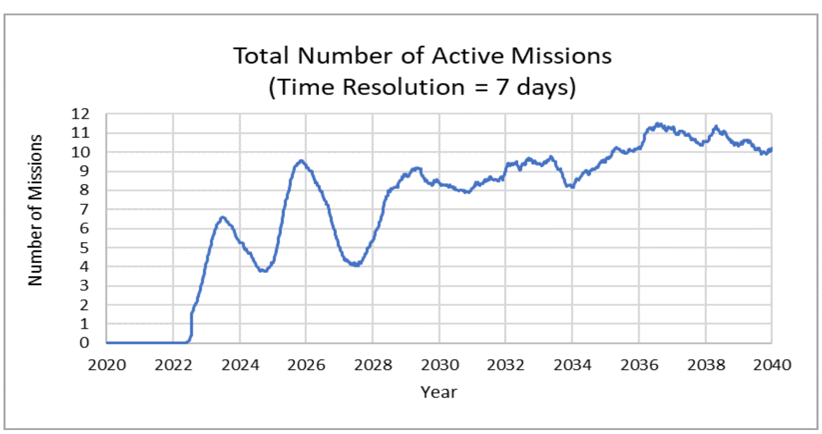


**Figure 2-2: Total number of active missions over analysis period**

Figure 2-1 shows the mean number of new missions being launched per year. The overall trend is a slow increase of the number of missions, year on year, with a relatively stable distribution. This is expected to be driven by lower cost access to the Moon, successful lunar landings enabling more appetite for lunar exploration missions and investment, more regular lunar transport opportunities, as well as a maturing lunar infrastructure enabling new mission capabilities and business models. Looking at the data per type of missions, there is a predominance of CubeSats, consistently from 2023 onwards, attributed to their low-cost nature enabling lunar mission opportunities for institutions/national space agencies, as well as acting as the first milestone in a "stepping stone" lunar programme of an emerging space nation. The flow of CLPS landers is also fairly constant, following the rhythm of the NASA CLPS programme. The same can be said for the NASA Artemis missions. Surface stations make an apparition towards the end of 2020s.

It is interesting to compare this constant flux of missions with the dramatic increase in number of simultaneously active missions over a week, shown on Figure 2-2. A few things are worth noting:

- From early 2020s to 2030s, peaks and troughs due to the "cargo" delivery effect. At least twice a year from 2023, several missions are to be carried on-board CLPS cargo missions or Artemis missions, creating a peak of demand for a short duration and nothing once those missions are finished.
- The second trend shows the start of sustainable presence around the Moon, which is likely to be dictated by In-Situ Resource Utilization (ISRU) discovery and the ability to sustain permanent presence on the Moon.

*2.3 Building the Case for Lunar Communications*

The evolution of data transfer needs of these lunar missions was also analysed, to identify the opportunity for a commercial lunar communications service. Figure 2-3 displays a steady increase in the daily data volume produced on the Moon up until the 2030, followed by a large jump in data appetite for lunar missions from 2030 onwards. Later lunar missions will have more capable technologies (e.g. higher data rates), more durable technologies (e.g. lunar night survival) and will have more ambitious and data hungry profiles (e.g. ISRU) - all contributing to this growth in daily data volume produced.

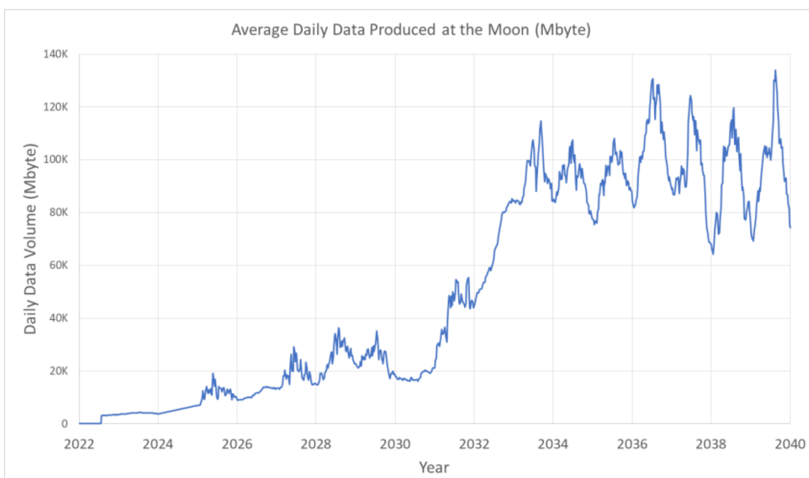


**Figure 2-3: Average amount of daily data produced on the Moon in Mb**

In Figure 2-4, results of the market analysis show that the majority of early activity occurs on near-side surface or orbital locations, with a rapid trend towards polar locations over time. It is also shown that the bulk of demand for data transfer is likely to be from polar locations. This comes from institutional missions, often more capable and more data-hungry, which tend to focus on the polar location at medium term. Polar regions also contain points of scientific significance such as the Aitken Basin, as well as considerable deposits of water ice and other volatiles. The number of missions to the far side of the Moon also increases over the years, a location where direct to Earth communication is impossible.

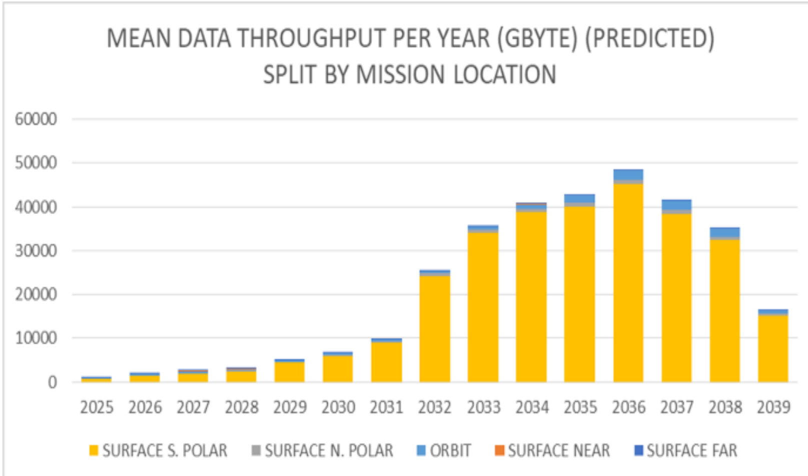


**Figure 2-4: Mean data throughput per year split by location**

*2.3.1 Communications Challenges of Lunar Missions*

Direct to Earth (DTE) communications are used by lunar missions in order to transfer their data back to Earth, whether they are in-orbit or on the surface. The lunar asset uses on-board communication systems with sufficient directivity and power to contact Earth directly, or transfer their data via a local surface relay, such as a lander, which then forwards on the communications using DTE.

NASA's Deep Space Network (DSN) is a global network of spacecraft communication ground segment facilities that support interplanetary spacecraft missions. It is the most commonly used infrastructure networks for DTE communications and is already facing a number of challenges, which will only be amplified as the volume of lunar missions grow in the near future.

When considering the implications of future lunar missions relying solely on DTE for communications, a number of potential issues can be identified:

- **Increased levels of loading**
  - The growth in mission volume from the New Space era already results in the DTE networks being routinely over-subscribed.
  - Capacity can be overbooked as much as 40% at the beginning of the scheduling process [8].
- **More stringent mission requirements**
  - Communication system technology improvements will lead to an increase of data volumes being collected and required data rates, placing more strain on DTE networks.
- **Line of sight**
  - DTE requires a direct line of sight between the lunar asset and Earth ground station
  - On the far side of the Moon, DTE is impossible.
  - It can also be limited on the polar surface or obstructed by lunar topography.
- **Complex scheduling process**
  - DTE scheduling processes can be lengthy and labour intensive – with lead times around 4 months [9].
- **On-board equipment**
  - Communications equipment with sufficient power and directivity to address the needs of the evolving lunar market will be heavier compared to that needed for transferring data through an orbital relay.
  - Lunar transportation via a commercial lander costs around $1M per kg, so every mass saving can directly translate into lower costs.
- **Flexibility**
  - User requirements frequently change depending on which phase of the mission the lunar asset is in (e.g. a lander in orbit operations has vastly different data transfer needs compared to descent and landing).
  - Usage of DTE networks can go from minimal to nearly continuous [8], which will become increasingly difficult to accommodate as the number of missions grow.

A lunar communications data relay service will aid in alleviating pressure on the DSN, while also ensuring lunar asset's needs are met.

## 3. Lunar Exploration Programmatic Framework

The return to the Moon is well underway, and ESA will lead Europe in making a significant contribution. The recently launched Orion spacecraft, including a European built service module, and extensive ground station network (ESTRACK), a module and avionics for the lunar gateway, the cargo lander Argonaut and many science payloads to be flown on commercial lunar landers.

Amongst all this, it has been identified that Europe should encourage commercialization and innovation in space activities. This is important to ensure European industry remains competitive globally. Not only leveraging ESA member state public budgets, but also encouraging venture capital and general private investment.

As the moon opens up to new missions, some of which are commercials services, there is potentially the need to provide communications, as more assets operate in the lunar vicinity and on the surface (both far and near side). ESAs approach for lunar communications is based in commercial partnerships. Buying a service, rather than owning hardware. To these ends ESAs human exploration directorate has initiated in partnership with SSTL from the UK, Commercial Lunar Mission Support Services (CLMSS) or in the first instance Lunar Pathfinder. In advance of the forthcoming Moonlight lunar communications and navigation constellation.

There have been two phases. The first was to invest in ground segment infrastructure, primarily adding and upgrading elements of ESTRACK. The second phase is the development of the Lunar Pathfinder spacecraft.

The mission is supported by ESA by becoming an anchor customer, enabling investment in the infrastructure needed to implement lunar comms services. On completion, SSTL will be able to sell the services on the commercial market and ESA will benefit from usage of the service as benefit in kind based on the initial investment. ESA is not a technical authority, which differs from the typical procurement approaches in the past, merely monitoring the performance of the service. Verifying compliance, not to design requirements, but so-called key performance indicators is the approach undertaken by ESA to manage the project.

## 4. Lunar Pathfinder Spacecraft and Service

### *4.1 Lunar Pathfinder Mission Profile*

Lunar Pathfinder is targeting a launch in 2025, with services to begin in 2026 for an operational lifetime of 8 years. It will be delivered to its lunar orbit by one of the eligible providers of NASA’s Commercial Lunar Payload Services (CLPS) programme. The spacecraft will operate in an Elliptical Lunar Frozen Orbit (ELFO), chosen as it provides long duration coverage of the lunar southern hemisphere, which we have identified as an initial hotspot of lunar activity. Lunar Pathfinder also has the ability to service missions operating on the far-side region of the Moon, enabling support for those with zero access to DTE communications. The Northern hemisphere will also experience coverage, but for shorter durations than lose of the Southern and Far Side regions.

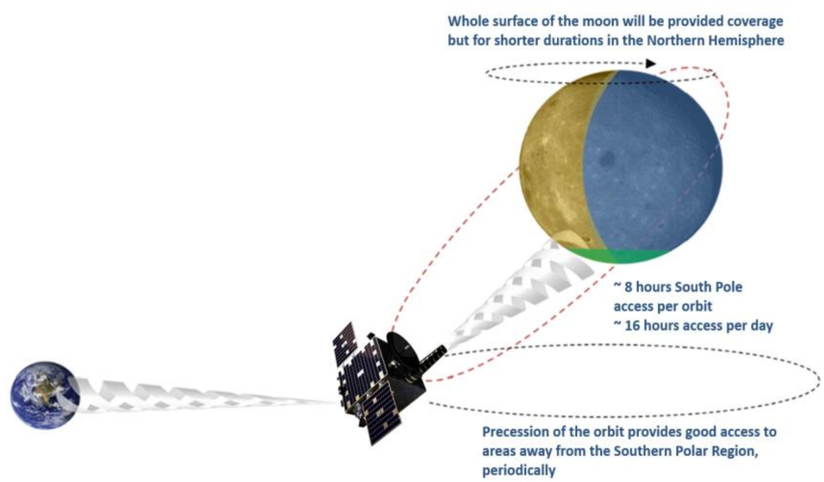


**Figure 4-1: Lunar Pathfinder orbit and coverage areas**

Lunar Pathfinder’s service is offered to any type of lunar asset, whether on the surface on the Moon or orbiting around it.

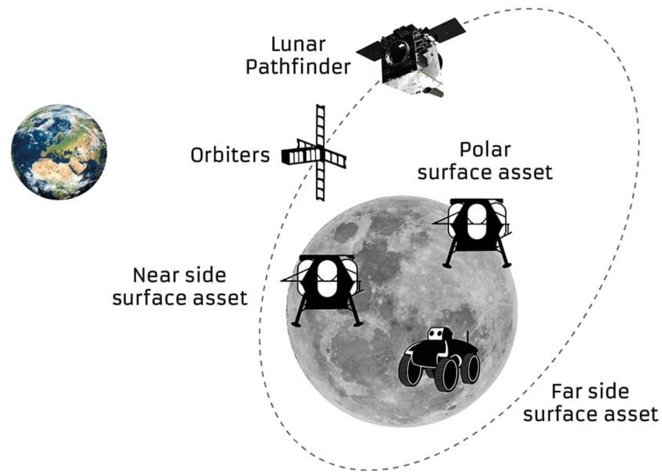


**Figure 4-2: Lunar Pathfinder customer asset locations**

*4.2 Addressing the Challenges Faced*

Lunar Pathfinder delivers value to users by providing an effective, low-cost solution to their communication needs, while addressing the shortfalls of DTE communications. Using the data relay service affords users:

- **Reduced operational costs**
  - Reduced need for contact with Earth ground station
  - Data from several users can be aggregated in the local relay through a store and forward architecture and share a reduced number of contacts with Earth ground stations, shorter in duration due to high-speed transfer.
- **Mass savings**
  - The on-board communication equipment required for data transfer with Lunar Pathfinder's proximity link is reduced in mass and complexity compared to that for DTE.
  - This translates into additional cost savings.
- **Performance improvements**
  - Lunar Pathfinder enables the same or improved communication performances (i.e. data-rates) with smaller communications terminals due to the proximity network.
- **Line of sight**
  - Enables missions to have uninterrupted connectivity during critical phases, not having to worry about obstruction of their communications link due to lunar topography.
  - Also unlocks exploration capabilities on the far side of the Moon, where DTE is unavailable.
- **Risk reduction**
  - Even with users whose primary means of communications is DTE (e.g. near side missions), compatibility with Lunar Pathfinder retires some of the risks involved with operating in the lunar environment.
  - Should a DTE link be unavailable (e.g. obstruction, reduced power) then communications could still be established using Lunar Pathfinder.
- **Flexible scheduling**
  - Lunar Pathfinder offers both autonomous or user-defined scheduling abilities, allowing spacecraft capacity and availability to be optimised for serving all users.

*4.3 The Spacecraft*

*4.3.1 Communications Payload*

Lunar Pathfinder is designed for a life duration of 8.5 years (when accounting for commissioning of the spacecraft and services). The platform accommodates a fixed solar array and 2 deployable solar arrays for power generation.

The Moon link payload of Lunar Pathfinder employs a Proximity-1 protocol that is capable of offering 2 simultaneously operational channels of communication for users:

1. S-band
2. Ultra-High Frequency (UHF)

The Proximity-1 protocol is designed to work with multiple assets in the same coverage area, and with a variety of assets of various performances (accommodating data rates between 0.5-2048kbps). The data rate can be dynamically adjusted over the session of a link in order to maximise the data throughput as the strength of the signal varies. All links will be controlled by Lunar Pathfinder, which means that each transceiver will only operate on one RF channel at a time and multiple assets will be using this single channel.

Data is then relayed by Lunar Pathfinder back to Earth ground station using the backhaul link in X-band.

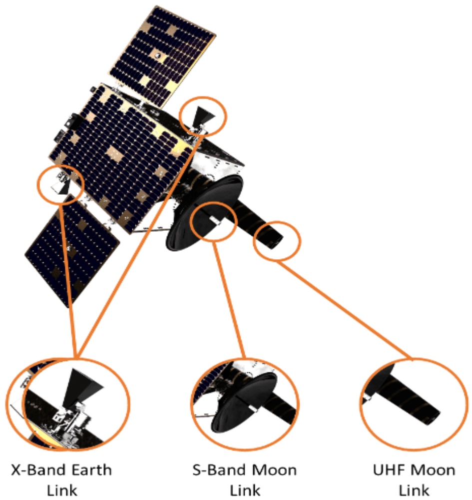


**Figure 4-3: Lunar Pathfinder communications payload**

*4.3.2 Lunar Pathfinder's Hosted Payloads*

There are also a number of hosted payloads onboard Lunar Pathfinder, in order to maximise the scientific output of the mission. The knowledge gained from these payloads will aid in augmenting future lunar mission capabilities.

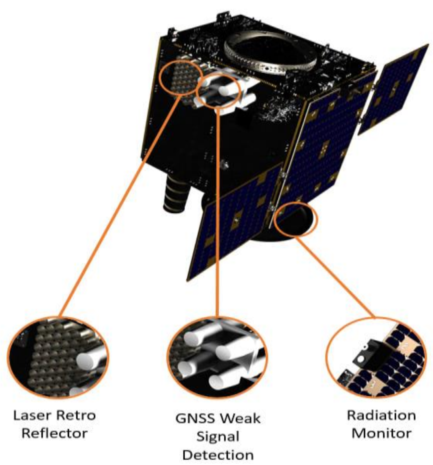


**Figure 4-4: Lunar Pathfinder hosted payloads**

- **Laser Retro Reflector**
  - Payload from NASA
  - Provides precise measurements of the Pathfinder's position, and to check the performance of GNSS
  - Data will be used by NASA to navigate its Artemis missions, and to further research in lunar science and the structure of celestial bodies.
- **GNSS Weak Signal Detector**

- Payload from ESA
- Experiment to investigate the potential of using Earth GNSS signals to augment lunar navigation capabilities.

▪ **Radiation Monitor**
- Payload from ESA
- Space weather monitor to understand radiation levels around the Moon
- This will help to inform decisions regarding future human exploration of the lunar environment.

*4.4 The Service*

The suite of communication services available from Lunar Pathfinder's portfolio can be viewed in Figure 4-1 below. Prior to contract signature for any of the packages, SSTL will work with customers to define the services best suited to their needs. Compatibility between the user spacecraft and Lunar Pathfinder will be ensured, while an estimate of the expected performance will be provided.

Looking at the operational services in Figure 4-1, Lunar Pathfinder has baseline options, which will be offered as soon as the spacecraft is commissioned, and services that are under development for future implementation. The implementation of these future services ensures that Lunar Pathfinder is able to respond to the communications needs of an evolving lunar market. More in-depth information on the service portfolio can be found in the Lunar Pathfinder Service guide on the SSTL website [10].

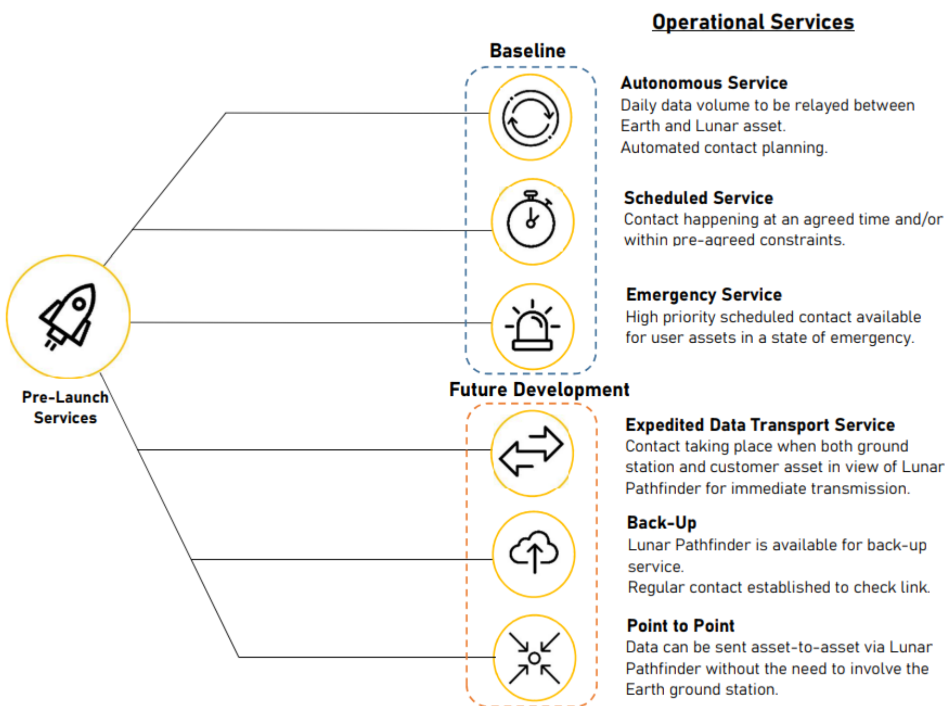


**Figure 4-5: Lunar Pathfinder services offered**

The communication service works on a store & forward architecture, allowing flexibility regarding the relative position of the lunar assets, the data-relay spacecraft, and the Earth ground station. Data is stored in the payload until links are available. Using this communications method, several benefits are unlocked:

- Commands can be sent to Lunar Pathfinder, destined for asset, even when the asset is not in view of Earth.
- Data can be stored at ground station until next access to Lunar Pathfinder.
- Data can be routed between lunar assets on sequential accesses without going via Earth.
- Duration and schedule for ground station accesses can be varied based on the amount of data to transfer and user operational requirements, reducing operational cost.
- Provides operational flexibility – users can work normal hours rather than standing up an out-of-hours team to wait for a link to be established

*4.4.1 Service Performance Levels*

The achievable data-rates with the Lunar Pathfinder communications services depends on both the relative position of the user to the Lunar Pathfinder spacecraft, as well as the performance parameters of the user terminals. Table 4-1 displays a summary of the achievable communication link performances.

**Table 4-1: Achievable communications performances**

| Link type | Channel band | FWD frequency | FWD data rate | RTN frequency | RTN data rate |
|---|---|---|---|---|---|
| Moon | S-band | 2025-2110MHz | 0.5kbps – 2Mbps | 2200-2290MHz | 0.5kbps-2Mbps |
| Moon | UHF | 390-405MHz | 0.5kbps – 2Mbps | 435-450MHz | 0.5kbps-2Mbps |
| Earth | X-band | 7190-7235MHz | Up to 30kbps | 8450-8500MHz | ≤ 5Mbps |

For more bespoke information on expected service performance, SSTL's Lunar Pathfinder Mission Builder Tool [11] allows users to input high level mission characteristics (location, mission dates, frequency band used, EIRP, G/T & data required per day) and receive a forecast of expected coverage and performance.

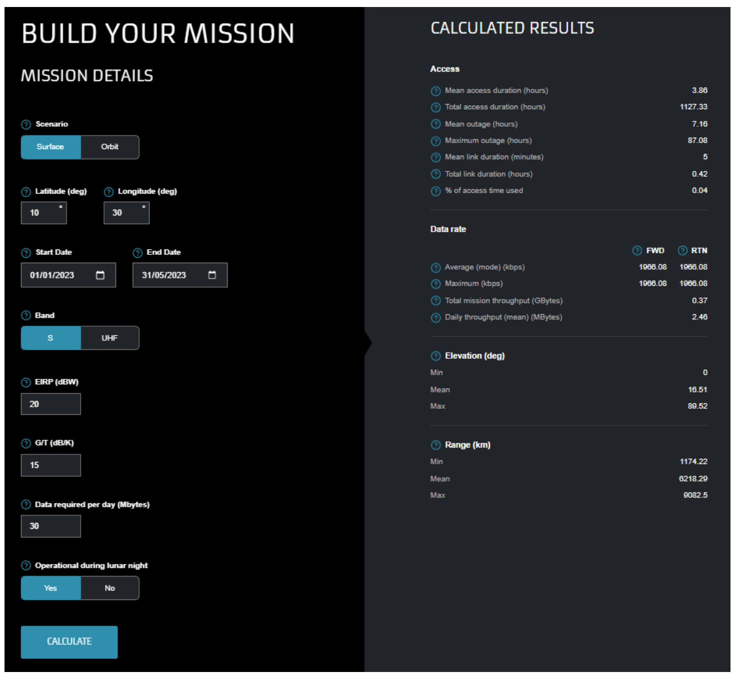

**Figure 4-6: SSTL Lunar Pathfinder Mission Builder Tool**

*4.5. Satellite Operations in a Lunar Environment*

Compared to traditional LEO missions, there are some significant differences in how spacecraft operations for a lunar mission need to be conducted.

The first key difference is that unlike a low earth orbit (LEO) mission, the pass times will not be at a similar time of day each day. Instead, over the course of a complete lunar cycle (28 days) the GS pass times will change over a 24 hour window. This make routine activities a little more complicated, as they will not necessarily take place at the same time and day each time they are performed. SSTL employs lights out operations and the same is baselined for Lunar Pathfinder. This means that routine tasks are automated and file upload and download will happen whenever the spacecraft is in communication with the ground. Out of limit (OOL) checking of logs and telemetry is also automated, triggering an SMS to the on-call team if any OOL are detected.

Another consideration is that there is no magnetic field around the moon and so Attitude and Orbit Control System (AOCS) sensors based on magnetorquers and magnetometers cannot be employed. The main attitude sensors are Star Trackers and Gyros for nominal operations with Sun Sensors used for Safe Mode. Reaction wheels are used for attitude control and all momentum offload is achieved using the hydrazine monopropellant propulsion system.

To gain a good understanding of the position of a spacecraft, in LEO the spacecraft will generally have a GPS receiver which allows GPS derived ephemeris to be generated and used for tracking. For a spacecraft in lunar orbit, an orbit determination (or ranging) campaign needs to be routinely carried out. This involves the ground station sending a signal to the transponder on board the spacecraft and then measuring the time between it being sent and a response being received. This is repeated at regular intervals and allows for ephemerides to be derived, which are in turn used both by the ground station for tracking and on-board the spacecraft to compute the AOCS guidance.

Both the momentum management and orbit determination activities need to be pre-scheduled on the ground and command files uploaded to the spacecraft in advance of the activities being performed. They will also require payload operations to be paused whilst they take place.

Lunar Pathfinder has a UHF band communications link for lunar communications with other assets. There are some significant restrictions on when this frequency band can be utilised, due to the shielded zone of the moon (SZM), which aims to safeguard radio astronomy on the far side of the moon. S-Band operations are not impacted by this restriction. The Lunar Pathfinder planning system manages all such restrictions when scheduling lunar communications links with customer assets.

The environment in which Lunar Pathfinder will operate is very different to that for a LEO spacecraft; there is a higher level of radiation which needs to be considered when designing the mission. From an operations perspective it means we expect to have approximately ten time more single event upset type effects and radiation induced anomalies. The spacecraft will need to be routinely checked to ensure flight software executables and libraries are not corrupted (for both the OBC and other modules which have firmware or software stored on them).

## 5. Global Lunar Ground Station as a Service (GSaaS)

Only few unmanned missions have been conducted to the Moon during the last decades and they were usually supported by expensive Agency owned Deep Space Antenna Networks (DSN) that were designed for much longer distances. Except for DSNs, only few antennas exist that can support lunar communication links today. Most of them are leftovers from the Apollo time, transformed old C-band antennas from the former Intelsat Communications network or large old LEO (Low Earth Orbit) antennas, mainly former ESTRAC 15m antennas.

Therefore, new communication infrastructure is needed to allow all missions to communicate between Moon and Earth. This deficit has barely been addressed and it has somehow been assumed that the infrastructure either exists or that industry quickly fills the void as it has happened for LEO NewSpace (KSAT$^{Lite}$). Given that purchasing a lunar size antenna has a lead time of at least two years such infrastructure cannot be made available on short notice even if funding is there.

KSAT has tried to integrate as many of the existing lunar capable antennas as possible into its network. Each site is equipped with identical baseband equipment that makes integration into the KSAT network simple. This way the KSAT API's can be used, and the stations can be offered as part of a GSaaS concept. This has the advantage that all KSAT antennas, optical telescopes, lunar partner antennas and future KSAT lunar antennas are addressable through one single interface. As a result all mission phases (launch, LEOP, orbit raising, standard operations) can be supported through this interface to the KSAT Network Operations Center in Tromsø, Norway.

KSAT also plans to purchase an initial set of three lunar capable antennas that are compliant to the NASA LEGS (Lunar Exploration Ground Sites) requirements. These will be 20-m sized antennas with S-, X- and Ka-band up and downlink capabilities. Since such dedicated lunar ground infrastructure does not exist today, one has the freedom to place it at the best locations minimizing the number of stations needed and guaranteeing continuous lunar coverage. At a minimum three stations spread evenly around the globe with about 120º longitude and within +/- 35º latitude of the equator are needed. This results in locations in the southwestern United States, Southern Europe, and Eastern Australia, much like the NASA DSN.

Independent of ground station locations the poles of the moon cannot be accessed during longer periods and lunar relay satellites are needed. Of course, these lunar relay satellites also need a link to the ground.

The main challenges for establishing a dedicated Lunar Ground Segment are:

1. Time of delivery: While one antenna has two years delivery time the entire network needs at least three years. In fact, it is not clear if the antenna manufacturing capacity needed to serve all missions exists.
2. High Investment cost: The LEGS compliant antennas a novel and therefore expensive. The entire investment is at least 50 million USD.
3. Spacecraft focus: All energy seems to go into the spacecraft. Even if it is understood that communication is needed no commitment is given that allows commercial investments of this size.

4. Clog up: A single mission with the firm requirement of continuous communications (e.g. manned mission), can use up the entire network.
5. Return of Investment: The long delivery time and the high investment cost leads to very high minute prices that are needed to make this a reasonable business case.

## 6. Conclusion

We are witnessing a rare moment in space exploration history - an inflection point. Traditionally viewed as a hidebound segment of the space industry, led by governments and national space institutions, there is an ongoing paradigm shift to a commercial exploration ecosystem. The early lunar market will be a hotspot of diversified global activity – payload delivery, mapping, prospecting, mining, and resource utilisation to name a few. A robust and sustainable economy requires cross-sector collaboration, supporting additional business opportunities and a cohesive lunar community. Lunar Pathfinder's communications service will be a facilitator to these market verticals, operating in the whitespace between them, augmenting their capabilities and unlocking a wider customer base for all.

The return to the moon is not without its challenges, however. It will require significant technological and logistical capabilities, as well as significant financial resources. It will also require international cooperation and collaboration, as a range of countries and private companies are involved in the efforts to explore and develop the moon.

Despite these challenges, the return to the moon represents a momentous opportunity for humanity. It has the potential to inspire and educate future generations, to drive technological innovation, and to deepen our understanding of the universe and our place within it. It is an exciting and ambitious goal, and one that has the potential to shape the future of space exploration for decades to come.

## References

*List of references*

[1] A. Thompson, It's Official: Water Found on the Moon, 23 September 2009, https://www.space.com/7328-official-water-moon.htmTral, (accessed 10/01/2023)

[2] Pieters, C & Goswami, Jitendra & Clark, R & Annadurai, Mylswamy & Boardman, Jodie & Buratti, B & Combe, J.-P & Dyar, M. & Green, Raquel & Head, James & Hibbitts, Charles & Hicks, Mildred & Isaacson, PR & Klima, R & Kramer, G & Kumar, Senthil & Esemu, Livo & Lundeen, S & Malaret, E & Varanasi, P. (2009). Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M3 on Chandrayaan-1. Science (New York, N.Y.). 326. 568-72. 10.1126/science.1178658.

[3] Colaprete, A. & Schultz, Peter & Heldmann, Jennifer & Wooden, Diane & Shirley, Mark & Ennico, Kimberly & Hermalyn, Brendan & Marshall, William & Ricco, Antonio & Elphic, Richard & Goldstein, David & Summy, Dustin & Bart, Gwen & Asphaug, E. & Korycansky, Don & Landis, David & Sollitt, Luke. (2010). Detection of water in the LCROSS ejecta plume. Science (New York, N.Y.). 330. 463-8. 10.1126/science.1186986.

[4] Honglei, Lin & Li, Shuai & Xu, Rui & Liu, Yang & Wu, Xing & Yang, Wei & Wei, Yong & Lin, Yangting & he, Zhiping & Hui, Hejiu & He, Huaiyu & Hu, Sen & Zhang, Chi & Li, Chunlai & Lv, Gang & Yuan, Liyin & Zou, Yongliao & Wang, Chi. (2022). In situ detection of water on the Moon by the Chang'E-5 lander. Science Advances. 8. 10.1126/sciadv.abl9174.

[5] PricewaterhouseCoopers (PWC), Lunar market assessment: market trends and challenges in the development of a lunar economy (September 2021)

[6] Northern Sky Research (NSR), Moon Markets Analysis 2nd edition – April 2022

[7] Euroconsult, Prospects for Space Exploration 3rd edition – November 2022

[8] Johnston, M.D., 2020. Scheduling NASA's Deep Space Network: Priorities, Preferences, and Optimization.

[9] stuart, jeffrey & Wood, Lincoln. (2017). SmallSat Navigation via the Deep Space Network: Lunar Transport.

[10] Surrey Satellite Technology, Lunar Pathfinder Service guide, https://www.sstl.co.uk/getmedia/9efe3cc5-6b5b-4fd1-bbd7-443bc2d21848/Lunar-Pathfinder-Service-Guide-V004.pdf, (accessed 11/01/2023)

[11] Surrey Satellite Technology, Lunar Pathfinder Mission Builder Tool, https://www.sstl.co.uk/what-we-do/lunar-mission-services/lunar-pathfinder-mission-builder, (accessed 11/01/2023)