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Commercial communication services for the Lunar Expansion

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Abstract

As lunar missions and activities beyond LEO increase, there is a growing need for commercial communication services in the cis-lunar region. While agency deep space networks are essential for high-end missions in the outer solar system, commercial services can efficiently support tracking, telemetry, telecommand and high throughput communications for special operations in the lunar vicinity. SSC has a rich history of supporting lunar missions over the decades, including THEMIS, MMS, LRO, DSCOVR, Beresheet and recently the Blue Ghost Mission 1 Lunar landing with its record-breaking 10 Mbps from Lunar surface. To cater to the evolving needs of commercial and agency missions in the coming decade, SSC is enhancing its ground station network for cost-efficient multi-mission lunar operations. Currently, SSC operates a 24/7 S-band TT&C (Tracking, Telemetry, and Command) network utilizing 13-meter class antennas. The network has been recently expanded to include additional assets for 24/7 X-band TT&C support. To further augment the basic network with higher performance capabilities, SSC is collaborating with partners to involve larger assets. Notable collaborations include the Irbene ground station in Latvia, involving VIRAC at VUAS, and VIRATEC, and the Johns Hopkins University Applied Physics Laboratory (APL). The partnership with Irbene exemplifies the adaptation of a radio telescope with TT&C chains for communication beyond LEO, and recent updates are included in the paper. This enhanced network employs common CCSDS interfaces, SSC's newly developed low-threshold-to-entry scheduling, and TT&C APIs based on standard IT practices. A future roadmap for additional frequencies and capabilities is also discussed.
Keywords: Lunar, TT&C, Operations, API

1. Introduction

As lunar exploration and commercial activities expand beyond low Earth orbit (LEO), the demand for reliable, cost-effective, and scalable communication services in the cis-lunar region and beyond is growing rapidly. Historically, deep-space communication has been dominated by government-operated networks such as NASA's Deep Space Network (DSN) and ESA's ESTRACK, which primarily serve flagship scientific and exploration missions. These high-end agency networks play a crucial role in operations beyond Earth orbit, with their outstanding performance critical during certain phases and conditions. However, the increasing number of commercial and agency-driven lunar missions creates a high load on government-operated networks and opens for the inclusion of commercial assets. Commercial assets are cost-effective and can provide a performance suitable for large parts of the mission timeline, thus offloading deep space assets for more critical support.

SSC aims to support the sustainable expansion of commercial and scientific activities on and around the Moon by addressing the growing communication needs of lunar missions. This paper presents SSC's vision and recent success for an efficient, interoperable, scalable and commercially sustainable lunar communications network, paving the way for the next era of lunar exploration.

2. The need for Commercial Lunar Communications Services

2.1 Growing Demand for lunar operations

Lunar exploration is entering a new phase, driven by international collaboration and commercial ambitions. Government-led programs, such as NASA's Artemis, ESA's Moonlight initiative, and ISROs lunar missions, are complemented by private enterprises developing landers, habitats, and resource utilization technologies. The presence of commercial players such as Intuitive Machines, Astrobotic, and iSpace underscores the shift toward a sustainable lunar economy. This shift necessitates a scalable communication infrastructure to accommodate not only governmental science missions but also commercial ventures seeking long-term operations on the Moon.

To support this growing activity, communication networks must evolve to ensure global lunar coverage, including polar regions and far-side operations. While large governmental networks will continue to provide essential services, commercial ground stations can offer complementary capabilities that support frequent and cost-sensitive missions, including high-data-rate downlink, navigation augmentation, and routine command uplink.

2.2 Key Communications Requirements

The requirements for lunar spacecraft communications differ somewhat with typical LEO missions, as the scenarios are more varying in lunar mission designs. Effective lunar communication services must fulfil several core operational needs:

- **Tracking, Telemetry, and Command (TT&C)**: Reliable uplink and downlink capabilities for mission control, spacecraft health monitoring, and contingency handling. Tracking is also important, particularly before and during critical events such as lunar landings and lunar orbit insertions.

- **High-Throughput Data Transmission:** Support for scientific payloads, imaging, and surface operations requiring large-volume data transfers. Surface operations are often limited to a lunar day due to the thermal situation, and it is critical to get maximum scientific value out of the limited time.

- **Always-Available, Low-Latency Command and Control:** Providing continuous low-latency capabilities for real-time operations, ensuring mission responsiveness during critical phases such as landing, surface activities, and navigation. This requires a network of antennas to provide gap-free communications with coverage overlap between the stations for safe handovers.

- **Interoperability with Existing Standards and improvements:** Adherence to CCSDS protocols and compatibility with existing agency networks to enable seamless mission integration. There are areas where standardization has not yet been fully implemented, and SSC add-ons or proposals for future standardization are in place.

- **Cost-Efficient Service Models:** Providing scalable solutions that cater to diverse missions, from small-scale payloads to large infrastructure projects. This includes aiming at the right performance for the right mission phase.

- **Experienced operator:** Although automation is a critical part of a well-functioning operational system, an experienced operator on top of the automation is needed to rapidly handle anomalies, perform workarounds, and make top level decisions in case of unforeseen events. Operator experience is also critical to the early design phases of a mission, providing guidance, RF compatibility testing etc to ensure a successful mission.

Table 3-1 Communication Frequencies for Lunar Communications

Radio Frequency (RF) Band	Lower Frequency	Upper Frequency	Comment
S-Band (Forward, Uplink)	2025 MHz	2120 MHz	
S-Band (Return, Downlink)	2200 MHz	2300 MHz	Note that for US territories this band is reserved for US Federal use and has not been granted licenses in recent time otherwise.
X-Band (Forward, Uplink)	7145 MHz	7235 MHz	
X-Band (Return, Downlink)	8400 MHz	8500 MHz	This is the section of the X-band reserved for Lunar and Deep Space. The EESS band is also available 8025-8400 MHz from the Moon.
Ka-Band (Forward, Uplink)	22.55 GHz	23.15 GHz	
Ka-Band (Return, Downlink)	25.50 GHz	27.00 GHz	This is the same band as used for the Earth Observation LEO data reception.

2.3 Performance Requirements – LEGS baseline

To establish a clear performance reference point for commercial lunar communication providers, NASA and other international space agencies have developed the Lunar Exploration Ground Segment (LEGS) performance specifications [1]. Although not a firm or complete set of requirements, these specifications serve as a benchmark for defining communication service requirements for lunar missions and have become a reference point for SSC's development of new lunar services. LEGS outlines necessary parameters such as frequency bands, G/T, EIRP, to ensure that commercial providers can offer services aligned with governmental mission needs. The integration of LEGS specifications into commercial offerings enables a more structured and standardized approach to lunar communications, supporting both scientific and operational mission requirements in a predictable and scalable manner.

From a performance perspective, the LEGS requirements target a middle ground between current commercial offerings of up to 13-m class antennas, and the high-end deep space antennas operated by agencies. The target for LEGS is serving missions beyond GEO and up to the 2 million km (border of formal "deep space"). The LEGS requirements are typically requiring 18-20 m antennas to be met.

Table 3-2 Top level LEGS requirements, from [1].

	S-Band	X-Band	Ka-Band
Downlink G/T	21-28 dB/K	31-37 dB/K	47.5 dB/K
Uplink EIRP (minimum)	81 dBW	86 dBW	89 dBW
Approx 3 dB Beamwidth	0.5°	0.1°	0.04°
Uplink Max Data Rate	10 Msps	10 Msps	40 Msps
Downlink Max Data Rate	10 Msps	150 Msps	500 Msps

3. SSC Experience in Lunar Mission Support

SSC has a long history of supporting deep-space and lunar missions, providing communication services for various agency and commercial spacecraft. By leveraging its global ground station network and deep expertise, SSC has enabled mission-critical operations, including telemetry, command, and high-data-rate downlinks.

3.1 Historical Support for missions beyond Earth Orbit

SSC's involvement in deep-space missions spans several decades, supporting numerous high-profile lunar and interplanetary missions. Some notable missions include:

- THEMIS B/C – ARTEMIS P1/P2: Supporting NASA's repurposed THEMIS spacecraft, which were placed in lunar orbit to study the Moon's magnetosphere.
- Lunar Reconnaissance Orbiter (LRO): Providing communication support for NASA's long-duration lunar orbiter.
- Deep Space Climate Observatory (DSCOVR): Operating at the Sun-Earth L1 point, SSC has provided TT&C services, including ranging, using its S-band capabilities.
- Beresheet Lunar Lander: Supporting the Israeli SpaceIL's lunar lander, demonstrating commercial lunar exploration.
- ESA SMART-1: Assisting in Europe's first lunar mission, which tested ion propulsion and new deep-space communication technologies. In addition to communications, SSC was the main provider of the spacecraft.
- Firefly Blue Ghost Mission 1 (BGM-1): Sole network provider for LEOP, Lunar Transfer, Landing and Surface Operations. Highest bitrate ever from the Moon surface, 10 Mbps on DVB-S2 link to 13-m apertures on X-band, demonstrated with the Firefly BGM-1 mission.

These missions demonstrate SSC's capability to support lunar operations, ranging from orbiters to landers, using its network of ground stations optimized for deep-space TT&C and data transmission.

3.2 Current Capabilities

Today, SSC operates a dedicated 24/7 TT&C service for continuous communication with missions beyond Earth orbit. The infrastructure consists of:

- S-band TT&C Network: Utilizing multiple 13-meter-class antennas for continuous spacecraft tracking and command operations.
- X-band TT&C and Data Downlink: Used for high-speed data transfer from lunar missions.
- Ka-band Expansion: Integration efforts are ongoing to introduce Ka-band capabilities for higher throughput lunar communications. SSC is currently investing in Ka-band uplink capabilities for the Irbene 16-m ground station.
- Collaborative Partnerships: Network expansion efforts include integrating larger aperture assets, such as the Irbene Ground Station (Latvia) and Johns Hopkins APL antennas, to improve coverage and support additional mission types.
- APIs for Mission Integration: Automated scheduling and real-time control of TT&C services through standardized CCSDS-compatible APIs.

These capabilities support a range of operational requirements, from routine telemetry and commanding to high-data-rate scientific downlinks. The continued expansion of these capabilities aligns with the increasing demand for commercial and scientific lunar missions.

4. Infrastructure enhancement for multi-mission Lunar Operations

4.1 Always on 24/7 TTC backbone

In recent years, SSC has expanded its capabilities with a three-station "Lunar Backbone" network in Western Australia, Santiago de Chile, and Hawaii. New 13.5-meter class S-band and X-band TT&C systems have been established in Australia and Santiago, and existing systems upgraded in Hawaii. This network, supplemented by stations in European longitudes, offers continuous 24/7 lunar connectivity. The 13.5-meter class has been demonstrated operationally with bitrates of 10 Mbps on X-band. Its relative smaller size allows faster acquisition and location of spacecraft compared to larger DSN apertures. The network aims to provide robust lunar asset management at a lower cost than traditional deep space networks.

Figure 4-1 Construction of new 13.5-m class antenna in Western Australia aimed for Lunar support with X/S TT&C.

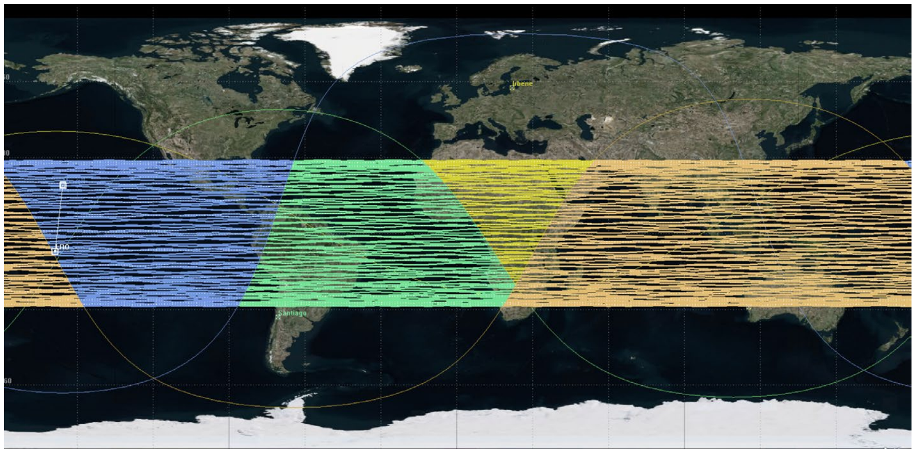

Figure 4-2 Example simulation of support for lunar mission (LRO in this case) from a four-station network consisting of Hawaii, Santiago de Chile, Irbene in Latvia and Western Australia. The coverage areas demonstrate that the spacecraft remains in view of at least one ground station at all times. The thin lines illustrate the full visibility, demonstrating that for large parts there are two stations, up to three in view at one time. Station overlap enables flexible operations with controlled and optimized handovers.

4.2 X-band TT&C

X-band TT&C has been used mainly on selected deep space probes in the past, while there seems to be an increased interest in transition to X-band TT&C (and future Ka-band TT&C).

The reasons are several:

- Congestion in S-band: Today, the S-band is highly utilized by an increased number of LEO missions which results in:
    1. Decreased performance and reliability on the link itself.
    2. A larger effort to perform regulatory coordination.
- S-band regulatory situation in US: The S-band downlink in the US frequency plan gives priority to US Federal operations. Before 2024, this was not firmly implemented, and allowance was granted for a majority of missions. After 2024, a number of missions have been declined operations with reference to Federal priorities. Such local constraints on S-band are globally raising further interest in X-band TT&C which is more uniform.
- Antenna gain: The antenna gains are higher in X-band, resulting in higher end bitrates for directed spacecraft antennas, such as the record breaking 10 Mbps from the Lunar surface that SSC recently demonstrated with the Firefly Blue Ghost Mission 1.

4.3 Ka-band TT&C

SSC has established Ka-band data reception on selected sites and is expanding with additional assets in the coming years, as the use of Ka-band is increasingly significant for Earth Observation satellites in LEO. SSC can also use these assets for high throughput Lunar links, e.g. video streams or payload data.

Ka-band uplink is a further step in the TT&C evolution, where SSC currently is investing in first capabilities through the upgrade of the Irbene 16-m antenna that will provide LEGS compliant Ka-band TT&C.

5. Augmentation with Larger Apertures into SSC Lunar Services

5.1 Upgrades and Inclusion of the Irbene Ground Station into SSC Network

Following the independence of Latvia, The Latvian Academy of Science created Ventspils International Radio Astronomy Center (VIRAC) which has been a part of Ventspils University of Applied Sciences since 2004. This center was built around two large aperture antennas, measuring 16 meters and 32 meters, formerly utilized for intelligence purposes. These antennas were in a deteriorated condition that necessitated significant refurbishment. The refurbishment was enabled under a European Union project to restore mechanical functionality and dish surfaces, introduce modern drive and antenna control system, outfit the antennas with cryocooled receivers, active hydrogen maser timing sources, capable digitizers and network equipment amongst other upgrades to achieve scientific excellence and state of the art in radio astronomy systems. Since then, the system has been primarily employed for astronomical research both in single antenna, local interferometer and VLBI measurements.

Figure 5-1 The 32-m aperture during an SSC-VIRATEC test campaign.
Photo credits to Emil Weslowski.

SSC and VIRAC have collaborated for several years, partially under ESA contracts, to explore the feasibility of integrating radio astronomy assets with TT&C beyond Earth's orbit. A set of proof-of-concept projects were conducted to demonstrate the capabilities of both the systems and operations. The confidence built in these demonstrations resulted in a commercial investment by SSC for TT&C integration, supported by adaptions of the antenna systems by VIRAC. Consequently, the 16-meter aperture will be upgraded to a full X/Ka-band TT&C antenna, while the 32-meter aperture will be adapted to serve as an S/X-band TT&C antenna, while still maintaining their capability for state-of-the art radio astronomy capabilities. The dual use by astronomy and space operations has significant synergies as the operational modes are quite different and can increase overall utilization of the assets, ensuring a sustainable financial model for such large apertures.

The Irbene assets will utilize similar equipment as the SSC 13.5-meter S/X-band system, ensuring compatibility and enabling the deployment of additional software features such as data transfer, scheduling, real-time status, and control in a manner consistent with other assets. A long-term agreement has been signed between Ventspils University of Applied Sciences, the spin-off company VIRATEC that will operate the commercial services, and SSC for inclusion in SSC's Lunar Network.

5.2 Collaboration with John Hopkins University Applied Physics Lab

SSC has been working in collaboration with the Johns Hopkins University Applied Physics Laboratory (APL) to use its 18.3-meter antenna with the SSC network for support on large antenna class lunar communication services. Historically, the APL antenna has provided communication to missions such as IBEX, Chandrayaan-1, LCROSS, and DSCOVR.

Figure 5-2 JHU APL 18.3 m S/X-band antenna supporting during Lunar Eclipse March 2025.

This antenna offers S-band uplink/downlink and X-band downlink capabilities, significantly enhancing SSC's lunar network by providing a high performing asset, increased redundancy, and expanded operational flexibility for lunar missions. The system features capabilities including:

- Multiple Spacecraft per Aperture capability.
- 4 simultaneous S-band downlink chains (2 each of LHCP and RHCP).
- 2 simultaneous X-band downlink chains (LHCP and RHCP).
- S-band uplink chains with dual 2kW klystron HPAs providing a high final EIRP of the system.

Participation of the APL antenna with the SSC network uses SSC-controlled baseband equipment, ensuring consistent service interfaces and streamlined operational control through SSC's Network Management Center (NMC). Recent support of a lunar mission successfully demonstrated this configuration.

5.3 Infrastructure Summary

The following table describes the performance for the described assets in this article. These are assets that are aimed towards SSC's Lunar network as well as traditional SSC TT&C assets.

Table 6-1 SSC Lunar Network Performance with LEGS specifications comparison.

Specification	SSC Typical Large LEO TT&C antenna	SSC 13-m X-band TT&C "lunar backbone" 24/7	Irbene RT16	Irbene RT32	John Hopkins University APL	NASA LEGS Requirement, Lunar
Location	SSC Sites in Punta Arenas, Santiago, Alaska, Hawaii, Kiruna (Sweden), Inuvik (Canada), Western Australia	SSC Sites, Australia, Chile, Hawaii	Ventspils, Latvia	Ventspils, Latvia	Laurel, Maryland	N/A
Diameter	7-13 m	13.5 m	16 m	32 m	18.3 m	~18-20 m
G/T S-Band[1]	~19-24 dB/K	26 dB/K	-	33 dB/K[2]	28.3 dB/K	21-28 dB/K
G/T X-Band[1]	~31-38 dB/K	39 dB/K	39 dB/K[2]	45 dB/K[2]	38.5 dB/K	31-37 dB/K
G/T Ka-band[1]	Up to 43 dB/K	-	48 dB/K[2]	-	-	47.5 dB/K
EIRP S-band	69 dBW	69 dBW	-	81 dBW	>80 dBW	55-81 dBW
EIRP X-band	-	88 dBW	86 dBW	86 dBW	-	65-86 dBW
EIRP Ka-band	-	-	89 dBW	-	-	89 dBW
Autotrack	S, X, Ka-band	S,X, Ka-band	X,Ka-band	S,X-band	S, X-band	S,X,Ka
Backend	SSC Rack, Cortex	SSC Rack, Cortex	SSC Rack, Cortex	SSC Rack, Cortex	SSC Cortexes	
Status	Operational	Australia operational, Chile and Hawaii in deployment	Work ongoing to be operational Q4 2025	Work ongoing to be operational Q4 2025	Operational	

[1]At 5 degree elevation [2]Final operational performance levels to be qualified after establishment.

6. Standardization, APIs and Operational Flexibility

6.1 API for Service Scheduling

Scheduling is an important interface for the service, where the contacts and the services are requested. Given the long heritage, SSC has supported a range of scheduling formats, including CCSDS Simple Schedule. However, today the preferred solution for scheduling for future and existing customers is to use a RESTful API to interface to the scheduler, which provides a clear way to interface with direct interaction and good observability. In addition to the RESTful API, there is also a web client, the "Customer Portal" where scheduling can be performed. This portal uses the same API as offered to the customers, also demonstrating the capabilities and power of RESTful API.

6.2 Ephemeris

The expected location of the spacecraft is needed for services such as scheduling, antenna pointing, and generic M&C. The preferred interface for this is through the Scheduling API, where a file can be provided with a description of the orbit. A large number of orbit description formats are supported, with the key ones being:

- OEM: The recommended format for Lunar missions. SSC is supporting OEMs with different central bodies (as in CCSDS specification), also enabling a clean description of lunar surface operations.
- TLE: Common format for earth-bound orbit descriptions, not recommended for lunar missions.

6.3 API for Real Time Status & Control

An interesting development for more varied operational scenarios is the new SSC add-on service of real-time status and real-time control. With these interfaces, customers can reconfigure links in real-time instead of having pre-defined transitions between different modes. Typical applications include in-orbit servicing, lunar missions, and other operations that may have less pre-defined link requirements.

The real-time API is based on standard web protocols to ease integration with customer MCCs. It is currently in operation, with ongoing additions of new features. The protocol is based on a WebSocket transport layer, where JSON or Protobuf packets are used for the real time data.

Table 7-1 Example of RTS and RTC parameters provided to the user

RTS Parameters	RTC Parameters
Antenna azimuth and elevation	Set UL/DL bitrates
Signal level	Set link configuration
Bitlock status	Enable / disable uplink
Framesync status	Restart sweep of uplink
Frequency that the radio has locked on	Enable doppler / ranging session

It should be noted that the RTS provided in this interface is for service overview and not purposed for flight dynamics. Ranging, doppler and antenna angles are provided in CCSDS standard TDM files for tracking.

6.4 New TMTC API for easy onboarding

SSC has today three main protocols for telemetry and telecommand in real time (in contrast with data reception that is delivered on a file server).

1. CCSDS SLE: A space industry format “Space Link Extension” that is highly used by agencies and larger corporations. High level of functionality but complex to start with.
2. Cortex Native: Used for many missions for many years. Based on a single vendors specification, medium complexity.
3. SSC Websocket TMTC: New SSC protocol with low complexity to get started with. Works well for all but very specific situations in complex scenarios.

It was noted that the existing protocols such as CCSDS SLE and Cortex native formats have their roles, but they are hard to interface with for entry level customers getting started. The SSC Websocket TMTC is a lightweight protocol based on CCSDS frames packaged in a JSON/Protobuf over a standard Websocket connection utilizing mTLS for encryption. This provides several advantages:

- Well known transport protocol that can easily be tested by common software tools such as Postman.
- Commonly used in web technology that demands high levels of e security, encryption, and monitoring.JSON and Protobuf are easy to decode.

7. Support of Lunar Landing of Blue Ghost Mission-1

In March 2025, Firefly Aerospace successfully achieved a lunar landing with the Blue Ghost Mission 1 lander. SSC provided critical communication support throughout all mission phases, including transfer, landing, and surface operations. The mission used S-band and X-band communications, utilizing an "always-on" strategy facilitated by handovers between multiple ground stations to maintain continuous coverage, with always at least one ground station in view. The radio on the spacecraft was provided by Vulcan Wireless [2].

With a highly varying mission profile, from the early commissioning of spacecraft to lunar injection, landing and finally surface operations, there was a need for dynamic link configuration which was effectively managed through SSC’s Real-Time Scheduling (RTS) and Real-Time Control (RTC) services. These services enabled rapid reconfiguration of the communication links, significantly enhancing operational agility and responsiveness to operational demands.

The global network supporting Blue Ghost Mission-1 included SSC stations located in Western Australia, Santiago de Chile, Hawaii, and partner facilities at Johns Hopkins University’s APL and Maspalomas through INTA. The Irbene station, with its 32-m antenna, would have been very suitable for supporting this mission but is currently under development and planned for operational service in Q4 2025.

Post-landing, X-band communication was vital in providing high-throughput data links necessary to maximize scientific and mission returns. The X-band link utilized a DVB-S2 configuration enabling Variable Coding and Modulation (VCM). This technology enables the spacecraft to rapidly change link configuration based on the local and dynamical conditions, where the ground network automatically detects and adapts to the selected link configuration.

Notable is that this 10 Mbps high-performance communication link facilitated the highest recorded throughput from the lunar surface, representing an important milestone in lunar communications capabilities.

8. Future development

8.1 Delay Tolerant Networking

Delay Tolerant Networking (DTN) technology has been successfully demonstrated in multiple space missions beyond Earth orbit, providing a reliable and flexible mechanism for data packet transmission through intermittent connections using a store-and-forward approach. SSC is currently exploring the potential benefits and implications of integrating DTN nodes directly at ground station facilities for lunar and other deep-space missions. DTN utilizes standard CCSDS transport protocols, making it readily implementable over SSC's current infrastructure, with the DTN endpoint then residing at the customer's mission control center (MCC). Incorporating DTN nodes at the ground segment may enhance overall network resilience, improve data transmission reliability, and facilitate rapid acknowledgment processes, which would be an advantage for high-data-rate links.

9. Conclusion and Outlook for Lunar Communication Commercialization

This paper has presented an overview of the capabilities and role of a commercial communication service provider in supporting the rapidly expanding lunar exploration activities. Commercial entities are increasingly being used to complement established government-operated deep space networks as lunar missions become more frequent and diverse.

SSC has demonstrated how commercially operated networks, particularly 13-meter class antennas augmented with larger apertures such Irbene in Latvia and Johns Hopkins University's APL, meet the requirements for lunar missions. SSC's recent involvement in Firefly's Blue Ghost Mission 1 exemplifies this potential, where SSC's ground network supported mission-critical phases from lunar transfer and landing to surface operations, achieving a record-breaking 10 Mbps data rate from the lunar surface. Such successes indicate the viability and value of commercial solutions in enhancing mission agility, resilience, and scientific return. Looking forward, SSC continues to expand its capabilities by investing in new infrastructure, advancing communication technologies, and creating strategic partnerships.

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