17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 537

NASA's Communications and Navigation Architecture Plans to Support the Return to the Moon and a Sustainable Lunar Presence

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Abstract

The National Aeronautics and Space Administration (NASA) Space Communications and Navigation (SCaN) Program is developing the communication and navigation support architecture for Artemis, NASA's Program to return humans to the moon. The Artemis missions will have increasingly complex communication and navigation (C&N) requirements driving SCaN's architecture to address both capacity and capability needs. The architecture will evolve bringing together technology and integrating capabilities from NASA, commercial, and international partners. This evolution will occur in phases to meet the needs for each Artemis increment.

Plans to increase capacity center on upgrades and expansions, including the Deep Space Network (DSN) Lunar Exploration Upgrades (DLEU) which are already underway, new Lunar Exploration Ground Sites (LEGS) and services, and Lunar Communications Relay and Navigation Systems (LCRNS). While DLEU is a government-led effort, NASA is seeking commercial services for a portion of LEGS capabilities and lunar relay. As the number of assets at the moon increases, and the community shifts to a sustainable presence at the moon, the complexity of C&N needs will require new comprehensive capabilities including lunar surface wireless based on commercial 5th Generation (5G) or later technology, lunar navigation services akin to our Earth-based Global Navigation Satellite System (GNSS) capability, and optical communications to aggregate large data volumes for return to Earth. These capabilities in aggregate reflect a concept for a cooperative set of C&N networks referred to as LunaNet, as well as NASA's intention to move toward a network architecture at the moon that is enabled by internet protocols and Delay/Disruption Tolerant Networking (DTN). SCaN is engaged with the commercial and international community to finalize the technical standards, specifications, and concept of operations for LunaNet to ensure a robust, interoperable framework is developed. Along with collaboration on technical standards, NASA is working to identify international partner contributions addressing capacity and capability needs.

One of the challenges NASA SCaN and the larger community faces, is the evolution of mission plans and requirements. SCaN has established a repeatable analyses process to quantify the proposed architecture's ability to meet mission demand and understand potential impact on non-lunar users, such as deep space missions that are users of the DSN. Each analyses cycle captures various "what-if" scenarios, and the outcomes are being used to refine the tactical steps to implement the architecture. Additionally, over each cycle, the analysis should employ lessons learned from previous iterations and become more efficient.

This paper describes in greater detail, the elements of the C&N architecture strategy, how SCaN will support the goals set out by the Artemis missions, and the associated challenges

Acronyms/Abbreviations

Acronym	Definition
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
ACD	Artemis Campaign Development
AFS	Augmented Forward Signal
AI	Agenda Item
BP	Bundle Protocol
BPSK	Binary Phase Shift Keying
C&N	Communications and Navigation
CCSDS	Consultative Committee for Space Data Systems
CLPS	Commercial Lunar Payload Services
CONOPS	Concept of Operations
CSIRO	Commonwealth Scientific and Industrial Research Organization
CY	Calendar Year
DLEU	DSN Lunar Exploration Upgrades
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
DSS	Deep Space Station
DTE	Direct to Earth
DTN	Delay/Disruption Tolerant Networking
ESA	European Space Agency
ESDMD	Exploration Systems Development Mission Directorate
FY	Fiscal Year
GDOP	Geometric Dilution of Precision
GHz	Gigahertz
GNSS	Global Navigation Satellite Systems
GoCo	Government-owned and Contractor-operated
GPS	Global Positioning Service
GSFC	Goddard Space Flight Center
HLS	Human Landing System
IETF	Internet Engineering Task Force
ISS	International Space Station
IT	Information Technology
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
KDP	Key Decision Point
LANS	Lunar Augmented Navigation System
LCRNS	Lunar Communication Relay and Navigation Systems

Acronym	Definition
LDPC	Low Density Parity Check
LEGS	Lunar Exploration Ground Sites
LEO	Low Earth Orbit
LNIS	LunaNet Interoperability Specification
LNS	Lunar Navigation Service
LTE	Long-term Evolution
Mbps	Megabits Per Second
MHz	Megahertz
NASA	National Aeronautics and Space Administration
NSN	Near Space Network
NSP	National Space Policy (U.S.)
OQPSK	Offset Quadrature Phase Shift Keying
PNT	Position, Navigation, and Timing
QPSK	Quadrature Phase Shift Keying
RAC	Requirements/Architecture Analysis Cycle
RF	Radiofrequency
RFI	Request for Information
RFP	Request for Proposal
SANSA	South African National Space Agency
SAR	Search and Rescue
SCaN	Space Communications and Navigation
SFCG	Space Frequency Coordination Group
SMD	Science Mission Directorate
SRD	Services Requirements Document
SV	Service Volume
T&V	Testing and Verification
UE	User Equipment
UHF	Ultra-high frequency
U.S.	United States
WRC	World Radiocommunications Conference
WSC	White Sands Complex

1. Introduction

The NASA Artemis Program is designed to execute a series of increasingly complex missions to the Moon, returning humans—including the first woman and the first person of color—to the lunar surface. Communications and navigation requirements for Artemis will be driven by the number of assets, their diverse locations, and the tempo of missions, including (but not limited to) lunar landing systems, rovers, the Gateway, science instruments, and eventually an all-encompassing Artemis Base Camp and sustained human presence (see Figure 1).

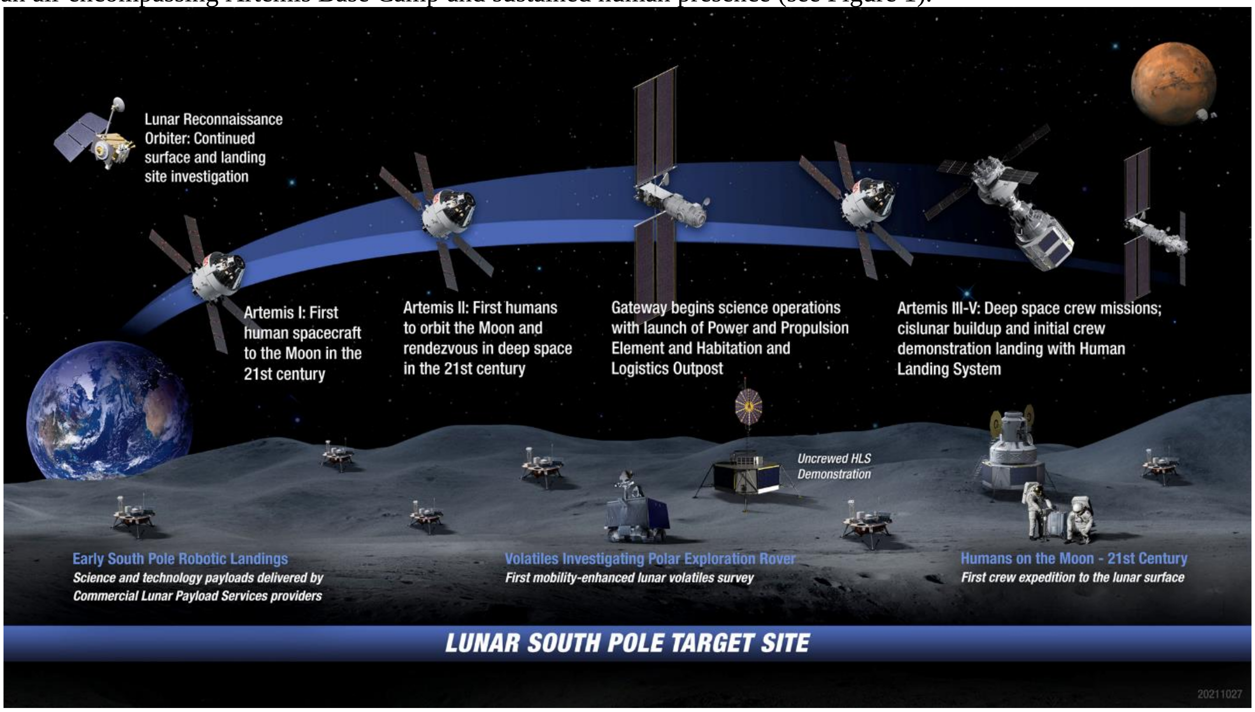

Figure 1: Artemis: Landing Humans On the Moon

NASA's Space Communications and Navigation (SCaN) program enables communications and navigation services for science and exploration missions and is responsible for ensuring the infrastructure capabilities are in place to meet the needs of the Artemis Program and its associated missions, vehicles, and users. The challenge will be to build a baseline set of resources augmenting the current Deep Space Network (DSN) resources planned for mission support in Cislunar space. NASA intends to exploit the success of the return of astronauts to the Moon to enable the first crewed landings on Mars, with the associated science and technology development required to achieve future science and exploration objectives. The Moon provides an opportunity to test new tools, instruments and equipment that could be used on Mars, including human habitats, life support systems, and technologies and practices that could help us build self-sustaining outposts away from Earth. The overall objective for the infrastructure is to create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface. The agency is looking to promote a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars. The return to the moon and future deep space missions are driving advancement of communications capabilities beyond what is possible with the current networks. SCaN will address the needs of Artemis by increasing capacity and integrating appropriate new capabilities to support expanded exploration at the moon and beyond.

2. Requirements and Analyses Approach

The Artemis missions represent significant peaks in demand on the SCaN networks. In 2021, SCaN initiated Lunar Capacity Studies as part of the process of assessing network supply and demand for the return to the Moon. The studies are intended to represent evolving communications requirements, map existing and planned communications infrastructure to those requirements and provide a comprehensive architecture assessment anchored in relative user satisfaction metrics and visualization. The loading assessment products identify if the planned network capabilities across the Near Space Network (NSN) and DSN will meet the needs of the Artemis mission set as well as continuing to satisfy the demands of other mission users such as the Science Mission Directorate (SMD). User and Network inputs are gathered to provide baseline network support scenarios which is coordinated with SCaN's current Lunar architecture plan and a set of "what if" cases examining different architecture solutions. The initial loading assessment cycle was tied to the Artemis Campaign Development (ACD) iterative Requirements/Architecture Analysis Cycle (RAC) and was used to establish a repeatable analysis process (Figure 2). Following this initial study the Loading assessment cycles will be completed on a 6-month cadence.

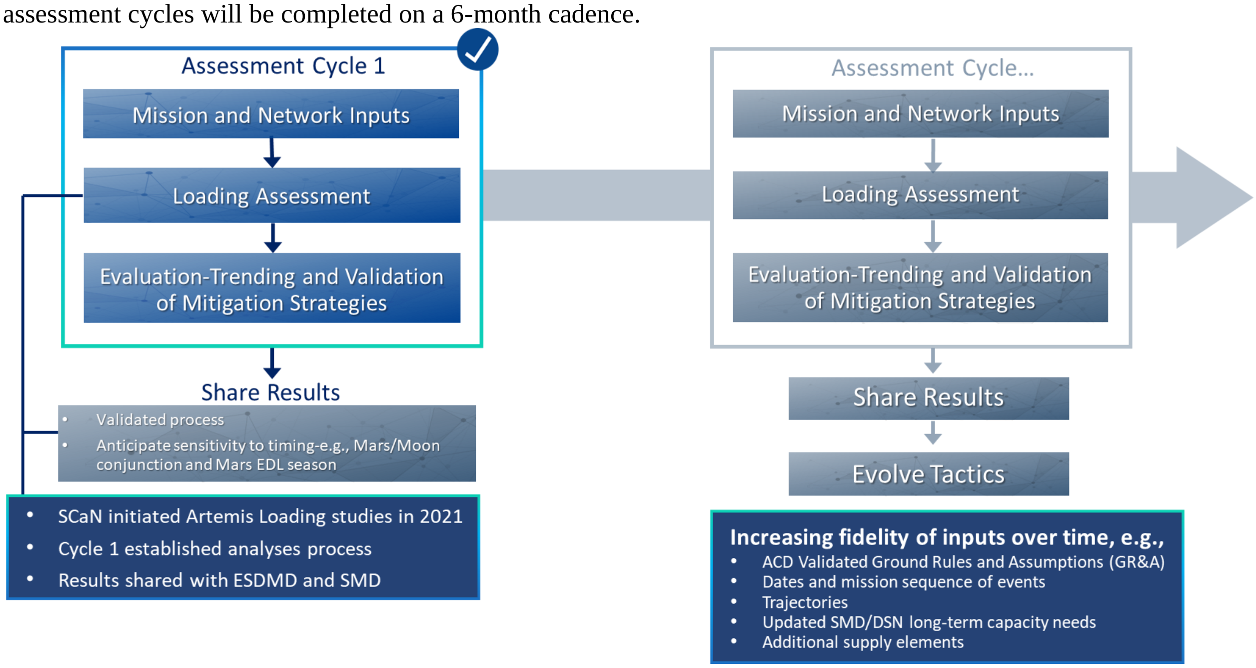

Figure 2. Lunar Capacity Study Cycles

Results of the studies are shared broadly within the Stakeholder community, particularly in SMD and the Exploration Systems Development Mission Directorate (ESDMD) which incorporates ACD. With each cycle the fidelity of the user and network inputs are increasing though focused engagement with the ACD team to refine mission requirements and assumptions. Collaboration between the teams ensures that the technical information, mission timelines and sequence of events, and Ground Rules and Assumptions defining the study are synchronized and up to date. The study results include notional schedules, user satisfaction and network utilization metrics, and possible DSN schedule overlaps for each Artemis increment (see Figure 3).

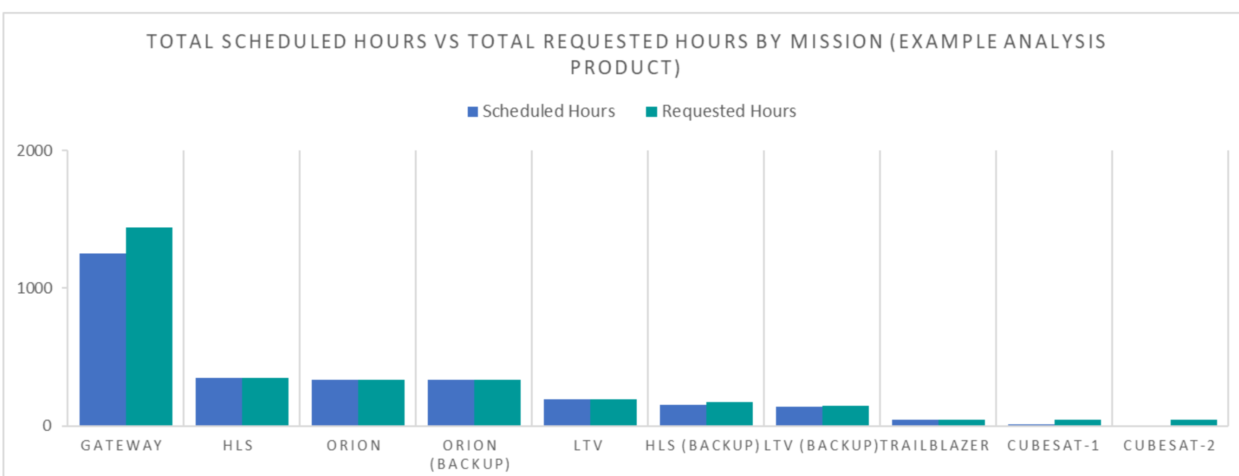

Figure 3: Example of Total Scheduled Hours vs Total Requested Hours by Mission

The results have informed changes to the planned support architecture, mission timing and mitigations for impacts to the DSN mission set.

3. Capacity

SCaN developed a strategy to immediately address architectural improvements for Artemis mission support necessary in the Artemis III through V timeframe where capacity gaps are driving requirements. The capacity will be increased by the addition of new C&N architecture and the enhancement of existing architecture. Network architecture additions and modifications will be accomplished through upgrades to the DSN – DSN Lunar Exploration Upgrades (DLEU), addition of new Lunar Exploration Ground Sites (LEGS), and deployment of lunar relay communications capability. In addition, NASA is intending to leverage international partnerships to provide robustness and resiliency to the planned support solution. Together these infrastructure improvements are referred to as NASA's "4-Point Plan" to address capacity gaps (See Figure 4).

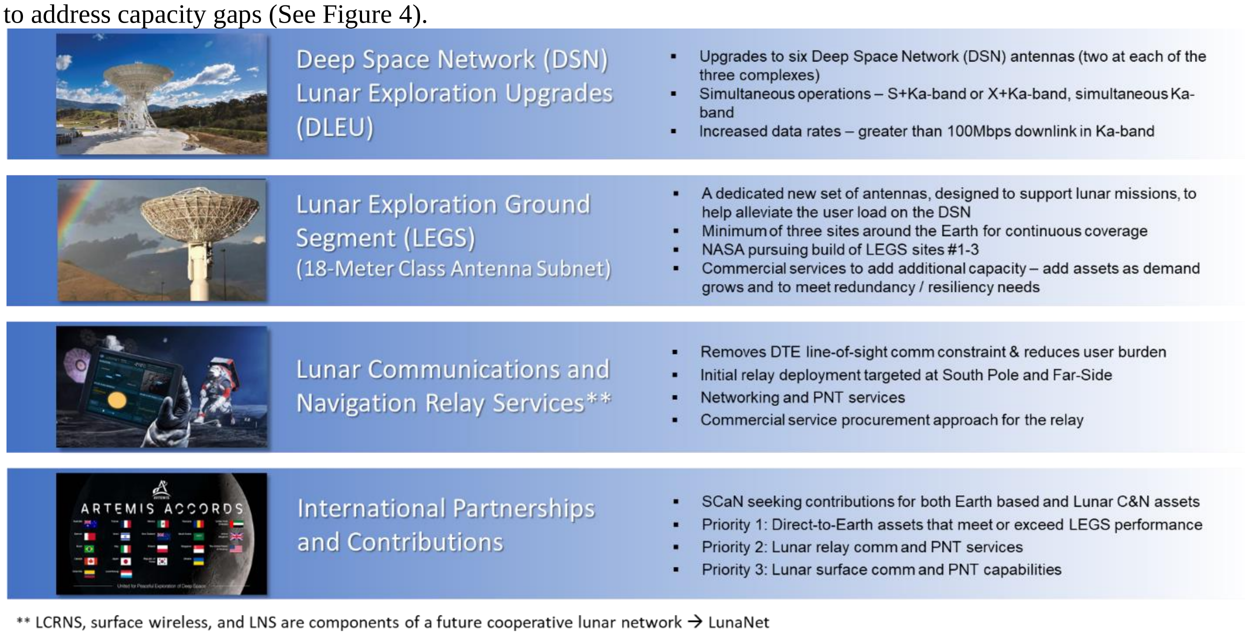

Figure 4: NASA 4-Point Plan

3.1. DSN Lunar Exploration Upgrades (DLEU)

A total of six antennas, two antennas at each DSN complex with be upgraded with near Earth K-band uplink. The DLEU upgrades have already begun with two of the six total upgrades complete by the end of 2022. Targeted capabilities are focused on concurrent antenna operations with configurations of either S+Ka-band or X+Ka-band (simultaneous S+Ka-band or X+Ka-band uplinks). Additional upgrades will allow for (1) low latency processing for data up to 150Mbps, (2) increased X-band uplink data rates to 5 Mbps, (3) increased Ka-band data rates (100Mbps downlink and 20Mbps uplink), (4) new uplink modulation formats (QPSK/OQPSK, filtered BPSK/QPSK/OQPSK), and (5) uplink data error correction coding (Reed-Solomon, LDPC). To minimize concurrent downtimes, the upgrades are being addressed one antenna at a time. Upgrades to DSS-26 and DSS-36 were completed by the end of CY 2022 and work on DSS-24 began in January 2023. Five of the six antennas are on schedule to be complete prior to the Artemis III mission—the first mission in the campaign to return humans to the surface. DLEU is described in detail in NASA's DSN DLEU paper [1].

3.2. Lunar Exploration Ground Sites (LEGS)

The LEGS project was established to provide "18-m class" performance (or better) apertures and/or associated services at multiple ground stations. LEGS is intended to augment DTE capacity for missions from GEO out to 2 million km alleviating pressure on the DSN 34-m assets given that the DSN will be supporting elements of Artemis along with a full portfolio of other Deep Space science missions. The initial three LEGS Sites will have 18-24-m X/Ka-band antennas which will be government-owned-contractor-operated assets. The primary function of these assets will be to support the 24x7 coverage requirement of the Artemis Gateway mission. LEGS Site 1 will be located at NASA's White Sands Complex (WSC). The South African National Space Agency (SANSA) will host LEGS Site 2 at Matjiesfontein, South Africa, while the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia will be NASA's partner for Site 3. The locations of these sites were selected to ensure full global DTE coverage for Gateway. NASA's goal is to establish the first 3 LEGS stations ahead of the Gateway launch.

Additional Information

FUNCTION	PERFORMANCE
Antenna Diameter (D)	D > 18m
Services	TT&C, CCSDS Forward and Return data, Radiometric tracking and antenna auto tracking angles
Transmit and Receive Polarizations	Tx: RHC or LHC Rcv: RHC & LHC
Antenna Travel Range	>360 deg Azimuth Continuous (TBR) 0-90 deg Elevation
Antenna axis Tracking rate	0.5 deg/s velocity (TBR)
Radiometric Tracking	Per CCSDS 414.1-B-2, Pseudo-Noise (PN) Ranging Systems
Radiometric Accuracy	Equivalent to DSN adjusted to C/No
Autotrack Accuracy	+/- 0.2 dB of beam peak (TBR)
Multiple Spacecraft Per Antenna (MSPA)	Up to 4 simultaneous return services per aperture (Max 3 Ka)
Timing Reference	short term stability better than 10^-14 (TBR)

Antenna System Radio Frequency Operating Regimes

Radio Frequency (RF) Band	Operating Frequency	
	Lower limit	Upper limit
S-Band (Forward)	2025 MHz	2120MHz
S-Band (Return)	2200 MHz	2300 MHz
X-Band (Forward)	7145 MHz	7235 MHz
X-Band (Return)	8400 MHz	8500 MHz
Ka-Band (Forward)	22.55 GHz	23.15 GHz
Ka-Band (Return)	25.50 GHz	27.0 GHz

RF Performance Criterion	Radio Frequency Performance (Forward)		
	S-Band	X-Band	Ka-Band
EIRP (minimum) [3]	81 dBW	86 dBW	89 dBW
Approx 3 dB Beamwidth[3]	0.5°	0.1°	0.04°
Forward Distortions [2]	1 dB max	1 dB max	1 dB max
Carrier Modulation	Direct PCM/PM PCM/PM/PSK, OQPSK, BPSK[1]	Direct PCM/PM PCM/PM/PSK, OQPSK, BPSK[1]	BPSK, OQPSK Filtered OQPSK[1]
Max Data Rate	10 Msps	10 Msps	40 Msps

RF Performance Criterion	Radio Frequency Performance (Return)		
	S-Band	X-Band	Ka-Band
G/T (minimum) [3]	28 dB/K	39 dB/K	47.5 dB/K
Approx 3 dB Beamwidth[3]	0.5°	0.1°	0.04°
Implementation loss [2]	2 dB max	2 dB max	2 dB max
Demodulation	Direct PCM/PM, PCM/PM/PSK, OQPSK, BPSK[1]	Direct PCM/PM, PCM/PM/PSK, OQPSK, BPSK[1]	OQPSK, Filtered OQPSK[1]
Max Data Rate	20 Msps	150 Msps	500 Msps

[1] Additional modulation schemes or data service types are optional

[2] GSFC CLASS link calculations use a 3dB implementation loss of which, the receive system is allocated 2dB and the transmit system distortions are allocated 1dB

[3] TBR pending finalization of antenna system requirements

Figure 5: Specification Sheet for LEGS Services

NASA is planning for additional ground station locations (Sites 4-6) and services to be provided by commercial providers. NASA intends to leverage the current NSN RFP for near-Earth commercial services to procure these additional LEGS. The commercial sites and service offerings are anticipated to include capabilities for S, X, and Ka-band transmit-and-receive services. However, NASA will not prescribe the way in which these services are provided. For example, the vendor may offer 3 antennas at a site or set of sites to meet the service specifications (see Figure 5). The NSN RFP was released in Q1 2023 and LEGS site locations and asset capabilities will be assessed to ensure the full capability and coverage needs are met. Potential locations for the commercial LEGS along with the government owned assets are shown in Figure 6.

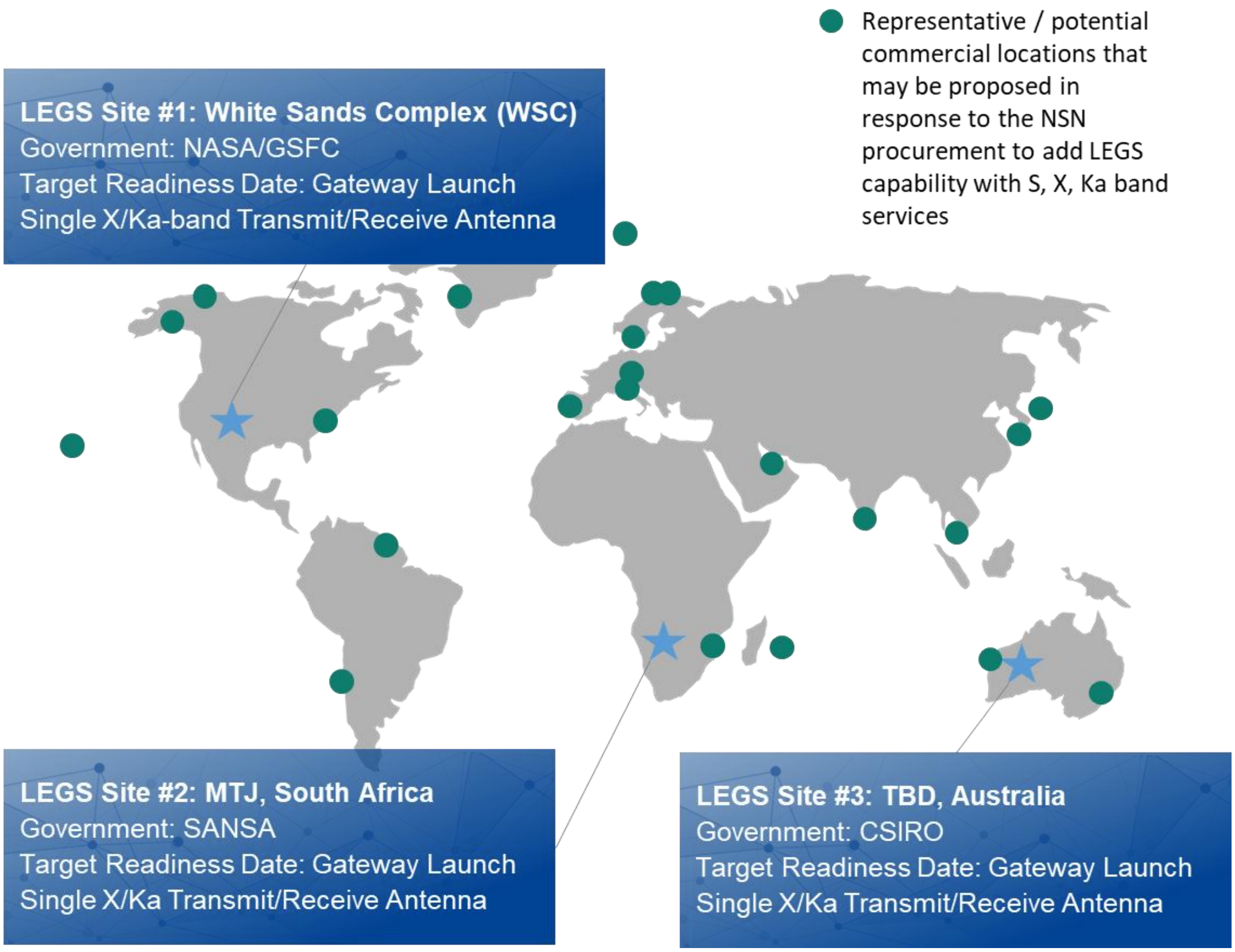

Figure 6: LEGS Site Locations

3.3. Lunar Relay

Some spacecraft and missions to the Moon will require relay spacecraft services to maintain a communications link with Earth. The primary benefit of lunar relay is in providing full coverage for the Lunar south pole. As the development for the relay progresses over the course of the Artemis missions, additional coverage for the Lunar far side and eventually full global coverage will become feasible. The relay will provide improved availability for missions by providing communications at landing sites without direct-to-earth visibility. Coverage of landing sites will enable SMD missions to the Lunar far side. The relay will support surface navigation requirements and enable long distance roving and other science needs for landed missions. SCaN is working toward procurement of commercial services for Lunar Communication Relay and Navigation Systems (LCRNS). Lunar relay services are intended to be fully end-to-end and therefore the providers will be responsible for data return to earth and delivery to NASA. Given that relay services will not require any NASA DTE support, these assets will provide communication links without impact to already overburdened DSN services. Lunar Relay service infrastructure is intended to support all the NASA Artemis mission users and international partner missions. Therefore, these and all other lunar relay services will be provided in compliance with the LunaNet Interoperability Specification (LNIS).

SCaN has developed a phased strategy for the procurement of relay services to allow time for industry to deploy services. The NSN RFP released in Q1 2023 defined two categories for commercial services being sought by NASA: (1) DTE services and (2) Relay services. Lunar relay is the focus of category 2 service for this procurement cycle. The phasing strategy was developed based on feedback from industry responders to the Draft of the RFP released in June 2022 [2]. This allows for the gradual increase in capability to reduce the initial burden of requirements for relay services. The RFP outlines service increments as Alpha, Bravo and Charlie for the initial operational capability for the relay [3]. A summary of the service provided in each increment is included in Table 1 and the service volumes indicated in the table are shown in Figure 7.

Table 1: Lunar Relay Service Summary

Increment	Alpha			Bravo				Charlie		
Service Type	Ka-band	S-band	AFS	Ka- band	S- band	AFS		Ka- band	S- band	AFS/ LANS
Number of Simultaneous Links	1	1	1	1	1	2	3	2	2	4
Forward/ Return Services	R only	F+R	F only	F+R	F+R	F only	F only	F+R	F+R	F only
Service Volume	SV1			SV1				SV2		
Min. % Coverage of an Earth Day	70%			75%	90%	70%	40%	75%	90%	40% [2]

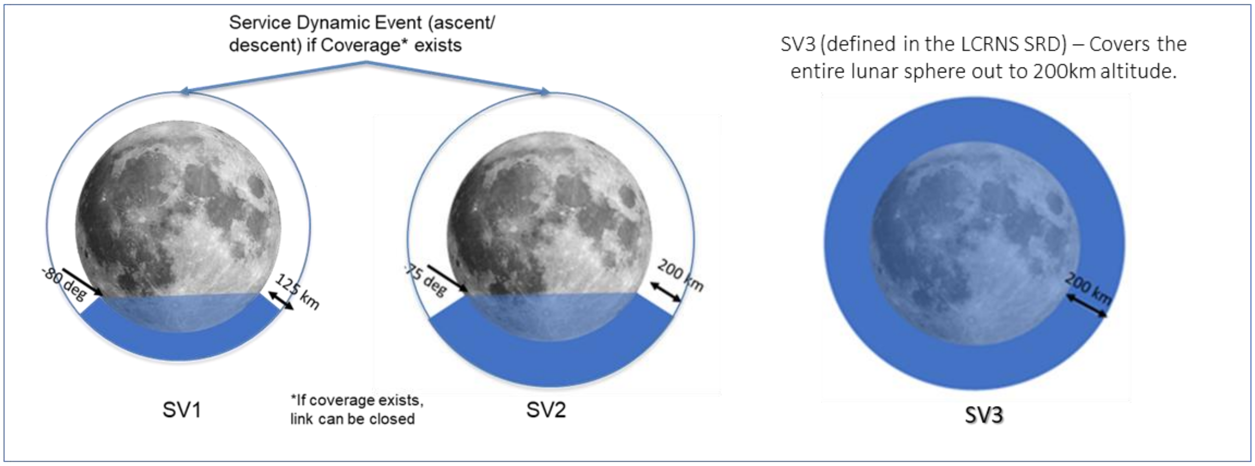

Figure 7: Service Volumes define for the Lunar Relay Service

The service requirements for the Lunar relay do not prescribe the number of nodes a service provider will need as long as the service attributes are met. The user data rates for Ka-Band service will be 1 Mbps to 10 Mbps for the forward link and 1 Mbps to 50 Mbps for the return link. In S-band data rates will be between 0.25 kbps and 2 Mbps for both forward and return links. Position, Navigation, and Timing (PNT) observational accuracy will be 0.93 m (3-sigma) at 10 sec for range measurements and 0.33 mm/s (3-sigma) at 10 sec for Doppler measurements. The phasing will ensure that a minimum level of service is in place for Artemis III and the framework is in place to allow a full set of initial operational capabilities are met in advance of Artemis V. Further development of the relay capability is anticipated after the completion of the IOC phase to meet expanding Artemis needs. An Enhanced Operating Capability (EOC) will be developed at the completion of the IOC increments. As the relay services develop, the coverage will increase to Service Volume 3 (SV3), which covers the entire lunar surface.

3.4. International Partner Contributions

NASA is pursuing international partnerships to augment and complement SCaN capabilities for Artemis support. SCaN is prioritizing international partnerships with DTE communications assets building additional robustness and resiliency into the planned ground infrastructure. DTE assets must have LEGS equivalent or better performance to meet NASA's Lunar needs. In addition to DTE contributions, NASA will evaluate partnership opportunities to leverage Lunar relay communications and navigation services. SCaN is also looking into opportunities for partnerships which offer lunar surface communications and navigation capabilities. SCaN is focusing on identifying and negotiating for the use of contributions which meet LunaNet interoperability standards as defined in the LNIS. Multiple international entities interested in contributing to Artemis have collaborated with SCaN to generate and refine the LNIS and/or plan to be compliant.

One example of the continuing collaboration between NASA and the international community is the collaboration between SCaN and the European Space Agency (ESA) regarding Moonlight. ESA's Moonlight Program aims at the development of Communication and Navigation capability and services deployed around the moon to provide dedicated infrastructure to support missions. NASA is in discussions with ESA to ensure that Moonlight services are available for Artemis. NASA has engaged regarding the Moonlight initiative through working groups focused on interoperability, service requirements, and developing a cooperative concept of operations. ESA engaged in the development the LNIS and have planned for Moonlight services will be compliant and therefore interoperable with the NASA LCRNS services. NASA was given the opportunity to review draft Moonlight service requirements and give technical feedback working toward alignment between the Relay services. Discussions to define a cooperative concept of operations (CONOPS) for sharing NASA and ESA relay services, much in the way DSN and ESTRACK services are exchanged are underway.

4. Capability

Beyond Artemis V, the complexity of missions increases, involving a more extensive build of up of assets, and demands on the networks will become capability oriented. The orbiting Gateway will continue to expand as habitats and additional capabilities are added. New vehicles, habitation assets, and support systems such as power generation units will populate the surface. Crew activities will be extended, with longer duration and farther ranging extravehicular activity by astronauts. SCaN is pursuing an architectural evolution of the Lunar network to meet these needs through (1) a 3GPP surface wireless solution for the moon, (2) augmented Navigation capability, and (3) Optical communication technology integration. The elements of SCaN's capability enhancement plan are summarized in Figure 8.

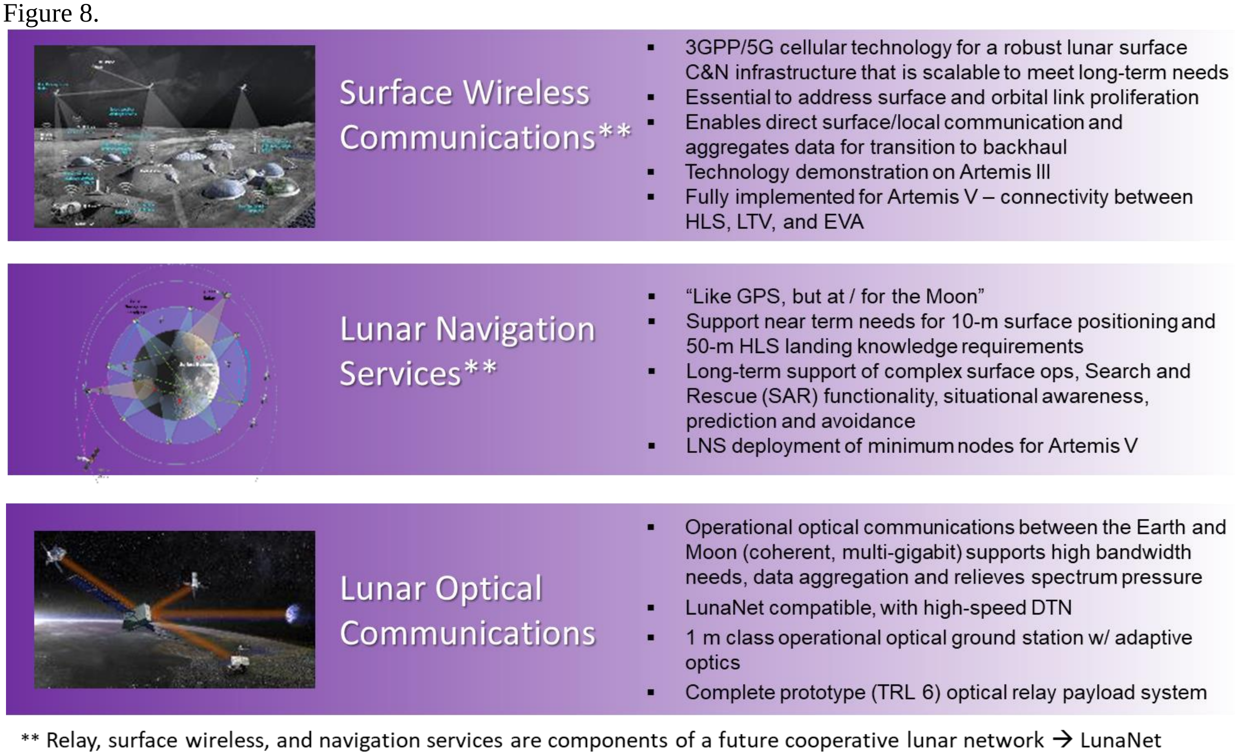

Figure 8: Evolution of Lunar Network Capabilities in the Post Artemis V Timeframe

4.1. Lunar Surface Wireless

The current Artemis surface communications architecture includes Wi-Fi communications for data and UHF communications for voice services. The operable range for these capabilities is 300-500m, depending on vendor antenna characteristics, placement, power, etc. This architectural approach is not sufficient to meet the desired Artemis CONOPS, particularly the ability of the Lunar Terrain Vehicle to traverse up to 10km and maintain connectivity with the lander/habitat, as well as the ability to support 2km walking limits from HLS that will be required by Artemis V. The desired surface architecture utilizes a 3GPP solution to meet Artemis needs [4]. SCaN plans to leverage the NASA partnership in 3GPP to make Lunar Surface Wireless communications possible. The Lunar surface communications use case is an ideal application for 3GPP technology given that lunar surface-to-surface communications is analogous to the terrestrial use case but with the User Equipment (UE) on the Moon. Lunar Surface wireless can be used for communications between Lunar surface elements and further enable PNT.

In 2020, a tipping point demonstration was awarded to Nokia to integrate 4G/LTE network assets for lunar surface communications between the lunar lander and a lunar rover. The objective of this demonstration is to verify the 4G/LTE network performance in two main scenarios: for short-range (~100-300m) and for long-range (up to 2 km) surface communications. Upon completion of the Nokia demonstration, SCaN will advance a 5G solution due to its operational advantages over 4G/LTE. To allow full implementation of a 3GPP solution for lunar surface communications, SCaN will need to secure the required spectrum allocations and address any other challenges as they arise.

Initially, SCaN is participating in a joint study with ACD to define the plan for Lunar surface network architecture. The team will assemble an aggregate model of requirements and current architectures (UHF, WiFi, Lunar relay, Gateway). The model will inform solutions to capability gaps in a mission-phased timeline. A plan detailing the architectural solution and a draft set of service-level user performance requirements will be developed. Implementation will be address after the completion of the study.

4.2. Lunar Navigation

The initial navigation service will be provided by nodes on the LCRNS relay assets, but eventually a dedicated Lunar Navigation Service (LNS) may be needed to meet the demands of the later Artemis missions. The end goal for Lunar Navigation is to have a GNSS-like constellation to provide LNS for surface and orbital users inside the Lunar Service Volume. One of the advantages of the service will be for Lunar elements to operate independently or nearly independently from Earth-based tracking. Requirements driving toward LNS include the 10-m surface positioning and 50-m repeatable HLS landing knowledge by Artemis III and autonomous PNT for Lunar users. To achieve this, it is thought that a full 24-node system is needed to provide 4+ signal availability to Lunar Surface users, however based on the results of previous studies defining Lunar architecture for PNT more work is needed to determine the minimum LNS architecture needed to meet long-term Lunar needs.

LNS is dependent upon critical infrastructure establishment including reference frames and precision timing devices and time dissemination. These infrastructure elements represent considerable work to establish and define particularly in the case of the Lunar global reference frame. This system will be analogous to the Earth reference coordinate system (WGS-84) which has evolved over decades. Highly accurate atomic clocks will be needed to provide accurate timing references. SCaN's Deep Space Atomic Clock (DSAC) is an ideal, demonstrated capability anticipated to be essential in development of LNS. LNS receivers will also need to be smaller and more powerful to be reduce burden for lunar users. The NavCube3-mini is a potential starting point for early adoption. Although LNS will be the most advantageous option for lunar navigation, the build up to reach this optimal state will take time. Until LNS can be implemented, Lunar users will be reliant on the initial capability offered by LCRNS, 2-way radiometric tracking with DTE assets, and other navigation sensors.

4.3. Optical

Optical communications will potentially be implemented as part of the phased architecture evolution. Optical capabilities will be driven by the large data rates, on the order of Gbps, required by Lunar users and only possible with optical communications. Optical communication will also support data aggregation, collecting data from cislunar users and delivering it to Earth via optical trunking vs. independent/individual radio frequency (RF) links from each user. Lunar data aggregation using optical frequencies will help to alleviate both RF spectrum and DSN congestion.

Optical links can serve many types of users and will be expanded in phases to meet needs as they arise. The initial Optical implementation phase will provide high-data rate trunk lines between Lunar relays and Earth Ground Stations. Subsequent phases could enhance intersatellite links between lunar relays, links between Lunar users and Lunar Relays, and links between Lunar surface users.

5. Policy / Standards / Interoperability

Moon exploration has emerged as a global strategic priority with both government and commercial missions driving development in support capabilities. This diverse set of interested parties contributing to Lunar exploration drives a collaborative solution for support architecture. To ensure that the Lunar network of communications architecture is collaborative and interoperable, NASA is working to define standards and specifications for Lunar service providers across the civil and commercial communities. Along with contributors from industry and other international partners, NASA has developed a concept for the interoperable C&N network in Lunar space known as LunaNet and drafted specifications to ensure cross compatibility.

The LNIS documents the interfaces and standards that the community is agreeing to use in the lunar environment, and so far, is a product of collaboration between NASA and ESA. Any friendly space agency or private company can contribute to the ongoing adjustment and refinement of the specification document. The current draft of the LNIS was released for feedback from commercial and international partners on September 12, 2022 and will continue to be updated and maintained by the community [5].

Delay/Disruption Tolerant Networking (DTN) is a cornerstone of the LunaNet concept/approach to interoperable communications and networking at the Moon. Existing DTN services have been demonstrated and developed internally by NASA as well as by other government space agencies and commercial entities. SCaN plans to utilize this existing technology and lessons learned from other applications to implement DTN for LunaNet. SCaN will implement the existing DTN protocols and continue to expand and standardize other DTN protocols with international partners. Two core DTN protocols that are already internationally standard are Bundle Protocol (BP) and the Licklider Transmission Protocol (LTP). Recently, updates to the standards for Bundle Protocol (Bundle Protocol version 7), BP security, and TCP Convergence Layer specifications were completed and have now been published by the Internet Engineering Task Force (IETF). SCaN will continue to standardize the remainder of DTN with international contribution via the Consultative Committee for Space Data Systems (CCSDS) for the civil space arena and the IETF for the commercial sector. International standardization of DTN will allow international partner space agencies to seamlessly contribute to DTN implementation for LunaNet.

Over the course of the Artemis campaign, the Lunar Region and communication lanes back to Earth will become more congested. The process of coordination for all the needed RF bands for Lunar Communications is underway. SCaN has a designated lead coordinating lunar frequencies – a Lunar Spectrum Manager – and has stood up processes and infrastructure, including a Lunar Spectrum Management portal/platform to coordinate across participating entities.

The Lunar Spectrum Management platform is being used to pre-coordinate with both Non-U.S. and U.S. Commercial users, Other Government Agencies, and other International Space Agencies before going to the ITU to negotiate the desired frequency allocations. Lunar Spectrum Management provides information on spectrum and applicable spectrum use, performs spectrum selection and analysis, uses knowledge of current and future spectrum use for technical coordination and impact minimization, tracks and prioritizes Lunar missions for spectrum coordination, and provides postlaunch interference resolution. The pre-coordination is intended to streamline the regulatory process because most of the work is done prior to engagement with the ITU for formal regulatory recognition.

The Lunar region is considered as part of the near-Earth domain and will therefore share frequencies with missions orbiting the Earth. Earth orbit is already very crowded with spacecraft using S-band. Therefore, it is in the best interest of Lunar users to use X and Ka-band frequencies for DTE communications. Also, due to the distance to the moon, much higher power is needed to close links and the typically low data rates of S-band frequencies mean contact durations must increase. Due to limited spectrum availability, frequency reuse can be applicable to alleviate spectrum congestion. Once a study has been conducted for missions considering spectrum reuse the mission can potentially implement this system. Some examples of missions and mission types eligible for spectrum reuse are Commercial Lunar Payload Services (CLPS), and Commercial SmallSats. SCaN will engage with domestic and international partners to coordinate frequency allocations to different Lunar communications services such DTE, Relay, Surface Communications, PNT, and Lunar Search and Rescue (SAR).

6. **Challenges**

The initial network enhancements are focused on increasing the capacity available for Lunar users. Until new assets capable of Lunar mission support are deployed, the DSN will be providing Artemis support in addition to supporting dozens of other deep space science and exploration missions. As SCaN works to bring new capacity online, the primary challenge for Artemis support will be to orchestrate and manage network usage across all users. This challenge will be a combination of (1) managing fluctuations in Artemis mission timing, (2) scheduling around critical events for other network users, (3) implementing lunar related network asset upgrades, and (4) arranging for regular network O&M downtimes.

Each Artemis increment incorporates multiple systems, elements and vehicles. Across these elements, schedule shifts or delays can affect overall increment timing along with various other external factors. For example, weather conditions shifted the Artemis I mission launch from late October to mid-November 2022. In addition, each mission supported by the DSN has a variable number of mission critical events requiring additional network support. Critical events require active schedule management to ensure none of these critical events are concurrent with the high demand Artemis mission timing. While adapting to changes within the mission community, SCaN is working to ensure that new lunar architectural elements will be delivered, and regular maintenance downtimes are accomplished to ensure assets are available when needed.

As the capacity is increased to meet needs, the nature of the challenges will shift toward ensuring enhanced capabilities can be provided. Given that significant time is required to plan for and deploy new network architecture, SCaN is working through the preparations to deploy capability-focused network evolution as user/mission needs develop during the later Artemis missions.

The build out of assets at the moon will challenge the Testing and Verification (T&V) approach previously used by SCaN. The number of test cases and compatibility tests is currently driven by the number of communications providers and interfaces. Further, the vision for LunaNet is for a multi-node interoperable network that includes not only NASA, but international, and commercial nodes and services. Testing with every communications asset or communication equipped node included in LunaNet may not be feasible as the number of providers and interfaces increases. SCaN will work to determine the appropriate level of testing across these various providers. Guiding specifications for services, such as the LunaNet Interoperability Specification Document are anticipated to facilitate a straightforward testing approach for compliant interfaces. Space communications networks incorporating multiple providers are not unique to NASA—the DoD is planning a hybrid space architecture which will need to address some of the same challenges as LunaNet.

RF spectrum needs in the Lunar sphere also present challenges. NASA must tackle issues with shielded zone science needs, and surface wireless allocations. The shielded zone of the Moon is very important in the radio astronomy realm, and as such, careful attention should be given to spectrum management in this region, balancing science needs with those of the human explorers. SCaN will need to analyze the impact to radio astronomy frequencies below 2GHz, intentional transmitter harmonics, and spurious emissions. SCaN will continuously engage with the radio astronomy community and the ITU-R to minimize impacts and reach a mutually beneficial decision.

SCaN will also need to pursue regulatory action to get frequency allotments for use on the Lunar Surface. In preparation, ITU-R Study Group 3 Working Party 3J (WP3J) is working on a new ITU-R Study Group (SG) 3 Question, contained in the WP 3J Chairman’s Report 3J/225/N27, to cover RF propagation considerations particular to lunar operations such as diffraction, reflections/scattering, multipath, terrain effects, etc. In addition, impacts to the shielded side of the lunar surface highlighting Radio Regulation (RR) 22.22 § 8 protections of the lunar shielded zone. There are unique radio frequency propagation aspects relevant to surface-to-surface and surface-to-space links that should be considered to aid in the development of novel long-term, compatible, reliable, and sustainable communications solutions. Further, WiFI and 3GPP, particularly 5G solutions are being considered for lunar surface operations. To date, the Space Frequency Coordination Group (SFCG) has come to an agreement to allow use of some frequency bands from the 3GPP and WiFi standards for lunar surface communications [6].

7. Conclusion

Current plans for near-term architecture evolution are well underway. To support Artemis, SCaN is already making upgrades to the Deep Space Network, beginning development of new ground stations and services that will be lunar-capable, pursuing lunar relay services, and working with international partners to put in place additional assets that complement NASA’s. For long-term sustained lunar operations, however, additional capabilities will be required. The fundamental needs are understood: (1) scalable surface-to-surface communications; (2) robust position, navigation, and timing infrastructure that enables precision landing, astronaut safety, and complex surface activity; and (3) optical communications links between the Moon and Earth to accommodate high data volume and reduce burden on the ground networks.

Lunar investments will feed-forward to Mars. SCaN has aligned itself with NASA’s Moon to Mars objectives. While retaining a focus on mission success for the Artemis Campaign in the near term, the Moon to Mars Objectives ensure a comprehensive framework will be in place to support Mars exploration goals in the future. The approach and lessons learned from the Artemis Campaign and lunar exploration will be leveraged toward the first crewed landings on Mars, with the associated Communications and Navigation infrastructure development required to support human exploration to Mars.

Time is required to prepare and implement these complex activities, so long-term budget planning is essential to success. SCaN has laid the groundwork for advancing a sustained human presence to the Moon and progressing onward to Mars, but additional effort and investment will be required to mature and deploy the necessary technologies, systems, and services to meet mission, program, Agency, and national expectations

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