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NASA's Deep Space Network (DSN) Lunar Exploration Upgrades (DLEU)

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Abstract

In the near future, the National Aeronautics and Space Administration (NASA) will return humans to the moon beginning the next era of human exploration. NASA's Space Communications and Navigation (SCaN) program will play a vital role in establishing communications and navigation support to realize the ambitious goals of the Artemis program. SCaN's overall lunar communications support plan will be covered in a separate 2023 SpaceOps paper: "NASA's Communications and Navigation Architecture Plans to Support the Return to the Moon and a Sustainable Lunar Presence." The four-point plan, as it currently stands, includes lunar relay services, a dedicated set of new ground stations, international partner contributions, and support through the Deep Space Network (DSN) and associated upgrades. This paper will have a more granular focus on the DSN and NASA's plans to upgrade and expand the network to be better suited for human spaceflight on and around the lunar surface. NASA's Deep Space Network (DSN) will be a critical communications component for the upcoming lunar activities. There will be multiple spacecraft, using different bands, and some of those spacecraft will be transmitting and receiving using multiple bands, requiring DSN support of S-band (2 GHz), X-band (7 GHz up, 8 GHz down), and K-band (22.5 GHz up, 26 GHz down). Since there may be more than one spacecraft in the beamwidth of the DSN antennas, the DSN support will require an extension of the DSN's capability to support multiple spacecraft using one antenna, expanding it to provide two simultaneous uplinks in the different bands at each antenna. Achieving this requires using new techniques for manufacturing the frequency selective surfaces, called dichroics, which steer the different frequency beams from and to the appropriate transmitting and receiving equipment, along with the addition of a new K-band uplink system. Additionally, due to the relative closeness of the moon from Earth (as opposed to the planetary missions the DSN supports daily), significantly higher data rates on both uplink and downlink are required are possible and desirable by the lunar missions, specifically up to 20 Mbps on the uplink and 150 Mbps on the downlink, both using Low Density Parity Check (LDPC) error correcting codes. And, again due to the relative closeness of the moon, there is a need for low latency data delivery of the high rate downlink telemetry which requires a change in the current DSN paradigm of delivering higher rate data with higher latency.

Keywords: Deep Space Network, lunar, space communications, networking, NASA

Acronyms/Abbreviations

Acronym	Definition
BPSK	Binary Phase Shift Keying
BWG	Beam Waveguide
CCSDS	Consultative Committee for Space Data Systems
CDSCC	Canberra Deep Space Communication Complex
CLPS	Commercial Lunar Payload Services
DCD	Data Capture and Delivery
DLEU	DSN Lunar Exploration Upgrades
DSN	Deep Space Network
DTE	Direct to Earth
FPGA	Field Programmable Gate Array
GDSCC	Goldstone Deep Space Communications Complex

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Acronym	Definition
GHz	Gigahertz
HLS	Human Landing System
HRCP	High Rate Common Platform
JPL	Jet Propulsion Laboratory
Kw	Kilowatts
LDPC	Low Density Parity Check
LEGS	Lunar Exploration Ground Segment
LEO	Low Earth Orbit
LRO	Lunar Reconnaissance Orbiter
LunaH-MAP	Lunar Polar Hydrogen Mapper
M	Meters
Mbps	Megabits Per Second
MDSCC	Madrid Deep Space Communications Complex
MHz	Megahertz
Msps	Megasymbols Per Second
NASA	National Aeronautics and Space Administration
NRHO	Near-Rectilinear Halo Orbit
OQPSK	Offset Quadrature Phase Shift Keying
PPE	Power and Propulsion Element
QPSK	Quadrature Phase Shift Keying
RF	Radiofrequency
SATCOM	Satellite Communications
SCaN	Space Communications and Navigation
SFCG	Space Frequency Coordination Group
SLE	Space Link Extension
SLS	Space Launch System
TESS	Transiting Exoplanet Survey Satellite
W	Watts
WAN	Wide Area Networks

1. Introduction

With the completion of the first Artemis mission (Artemis I) in December 2022, NASA is well underway, executing against its plan for human lunar exploration. Communications between the various lunar spacecraft, both human and robotic, and the Earth will require all of NASA's Space Communications and Navigation (SCaN) network services.

A core component of this support is NASA's Deep Space Network (DSN). To meet lunar mission requirements, the DSN Lunar Exploration Upgrades (DLEU) task will increase data rates through targeted key updates. First, DLEU will provide K-band 22.5 Gigahertz (GHz) uplinks at two antennas per complex; these uplinks will be able to transmit simultaneously with either of the existing S- or X-band uplinks, while the respective downlinks can be tracked. This requires designing and implementing new frequency selective mirrors (dichroics) that reflect one band and pass the other band. Second, the uplink data rate capability will be increased to 20 Mbps, and higher order carrier modulation capabilities – Quadrature Phase Shift Keying (QPSK) and Offset Quadrature Phase Shift Keying (OQPSK), both filtered and non-filtered – will be added. Third, the ability to decode Low Density Parity Check (LDPC) error correcting coding at rates up to 150 megabits per second (Mbps) will be added to the downlink equipment to support the required high telemetry data rates. Finally, the data delivery capability (delivering the telemetry data to the mission operations center) will be significantly increased to provide up to 150 Mbps low latency (less than 10 seconds); this will require both increases to the Wide Area Networks (WAN) from the DSN complexes and the DSN data routing capability.

This paper provides a summary of the NASA lunar exploration plans and a high-level description of the current DSN capabilities. Details of the DLEU implementations are provided, and the challenges that are being addressed are discussed.

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2. DSN Overview

Established in 1963, the DSN provides a communications infrastructure for all of NASA's robotic missions beyond Low Earth Orbit (LEO). The DSN's prime responsibility is telecommunications for NASA missions, but also provides support for international partner spacecraft as well as scientific investigations through radio astronomy, radio science, and radar activities.

2.1 Antennas

The three DSN complexes are stationed at approximately 120-degree longitudinal separations around the globe to provide continuous coverage for mission spacecraft spread throughout the solar system. Two of the complexes are in the Northern Hemisphere, Goldstone Deep Space Communications Complex (GDSCC) in California, and Madrid Deep Space Communications Complex (MDSCC) in Spain; the third is in the southern hemisphere, Canberra Deep Space Communications Complex (CDSCC) in Australia. Each of the three sites operates the entire network during their day shift, an operational approach dubbed "Follow-the-Sun" which improves the cost and personnel efficacy of the network. Each DSN complex has multiple large antennas capable of enabling continuous radio communication between several spacecraft and Earth. Each site consists of one 70-meter antenna and several 34-meter antennas, each equipped with ultra-sensitive receiving systems. The 34-meter antennas can provide communications in the Ka-band of the spectrum in addition to X-band, which increases the possible throughput for missions returning their data to Earth via the DSN.

Additionally, there are three DSN development and test facilities: DTF-21 in California, the transportable Compatibility Test Trailer CTT-22, and the Merritt Island Launch Area (MIL-71) at Kennedy Space Center [1]. The DSN is managed and operated by the Jet Propulsion Laboratory (JPL) on behalf of NASA.

2.2 Mission Types

The DSN supports interplanetary spacecraft missions, radio astronomy, radar astronomy and related observations. As of 2023, the DSN supports approximately 40 different spacecraft for missions ranging from geostationary distance to spacecraft outside the solar system, such as Voyager I and II. The Network Operations Control Center routes command data and serves as the endpoint for the distribution of tracking and telemetry data [2]. For over five decades, the DSN has served robotic missions. This paradigm has shifted with the beginning of the Artemis Program, and the program is navigating the balance of demands from two distinct mission communities—science and exploration—the latter of course entailing implications related to support of humans. DSN recently (November-December 2022) successfully provided tracking support to Artemis I and the Orion capsule. DSN has provided support for the Lunar Reconnaissance Orbiter (LRO) and will also be supporting future lunar missions including NASA's nanosatellite orbiter mission Lunar IceCube, planetary science mission Lunar Polar Hydrogen Mapper (LunaH-MAP), and lunar orbiter Lunar Trail Blazer, among others.

2.3 Radio Frequency Bands

To comply with Space Frequency Coordination Group (SFCG) recommendations, the DSN supports the near Earth and deep space S-, X-, and Ka-bands. This allows uplinks (Earth-to-space) and downlinks (space-to-Earth) to be phase coherent, if the spacecraft supports coherent operations. This coherency can be with the same frequency band or different frequency bands (e.g., X-band up and Ka-band down) [3].

~~3.~~ Artemis Network Support Requirements

The primary driver for increasing capabilities in the lunar domain is the Artemis Program. Space Policy Directive 1 states that NASA will "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations" [4]. Two phases have been defined for the Artemis program: (1) return to the moon and human landing, and (2) establishing a sustainable long-term presence on and around the moon.

One of the critical elements in the Artemis program is the Gateway, a space station for Artemis crew to live and work on a variety of science investigations and features docking ports for other spacecraft. Gateway's Power and Propulsion Element (PPE) module is a solar electric propulsion spacecraft (60 kW) that will serve as the direct to Earth (DTE) and landed assets communications hub [5]. Artemis missions will evolve into a sustained lunar presence, and therefore a continuous demand, for communication and navigation capabilities.

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The first human return mission to the moon represents a driving scenario for communications and navigation capability. The mission duration is expected to be 28-34 days with over six days of human activity on the lunar surface. Multiple independent vehicles will be operational, including the Space Launch System (SLS), Orion, the Human Landing System (HLS), surface power system, as well as deployed hosted missions including CubeSats and parallel Commercial Lunar Payload Services (CLPS) activity. This level of activity drives the need for multiple simultaneous links, particularly given the desire for hot backup on crewed elements. The Orion crew capsule will be launched separately on the SLS, and the HLS will be commercially launched and delivered. Communication and navigation support extends from launch to re-entry and splashdown with significant key events requiring communications, tracking, and navigation support – lunar orbit insertion, descent, landing, ascent, orbital maneuvers, and maintenance. Expectations for sustained presence will drive further communications demand including 4k video, telemedicine, complex remote operations, and astronaut health and safety.

A notional view of the Artemis systems, lunar operations, and essential communications and navigation services is provided in Figure 1 below.

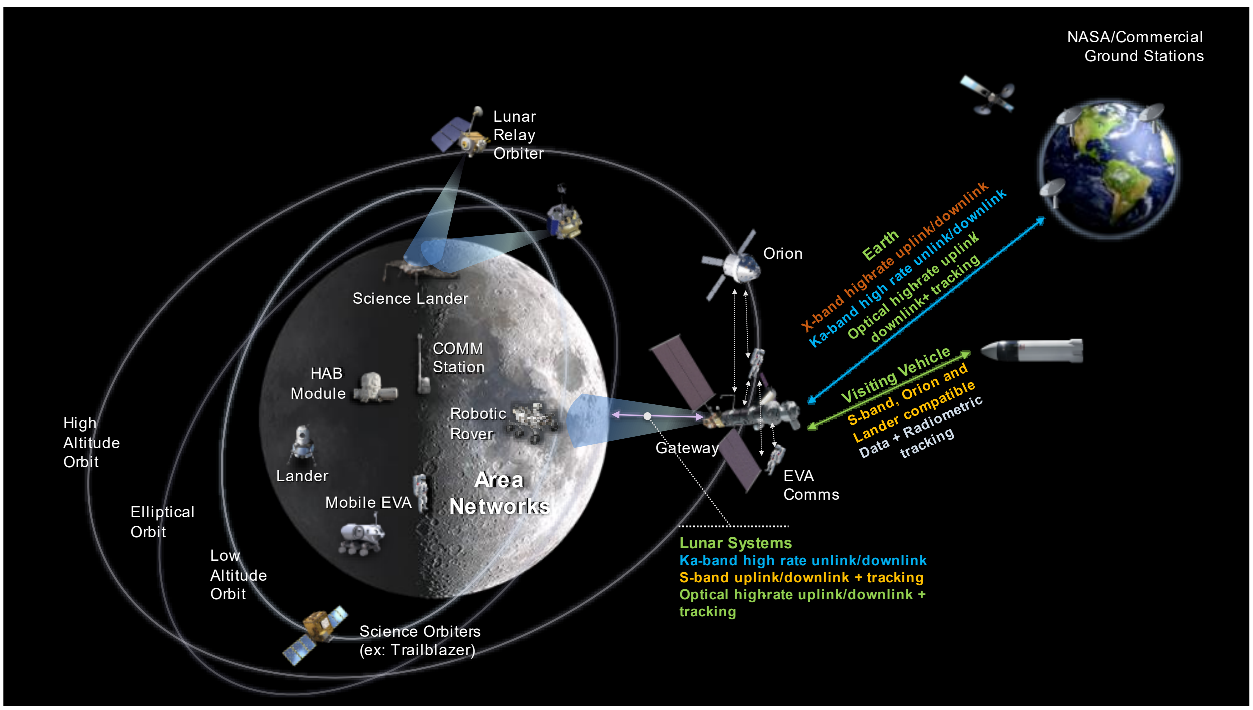

Figure 1: Artemis Conceptual Communications View

Gateway requires continuous X and Ka-band support: X-band uplink and downlink services will be used while uncrewed, and Ka-band uplink and downlink services will be needed from two weeks before the launch of astronauts on SLS through splashdown (to the maximum extent possible). Orion requires continuous low-rate (S-band) service in transit both to and from a near-rectilinear halo orbit (NRHO). Human Landing System (HLS) is expected to need continuous low-rate S-band services for uncrewed missions*, as well as continuous high-rate Ka-band services for crewed missions. The frequency bands for Artemis mission elements supported by DSN are documented in **Table 1.**

Table 1: Artemis Mission Elements and Frequency Bands

Mission	Mission Elements	Frequency Bands
Artemis I	Orion	• S-band
Artemis II	Orion	• S-band
Artemis III	Orion HLS	• S-band (Orion and HLS) • Ka-band (HLS)

* Future HLS providers may be discouraged from using S-band in keeping with SFCG recommendations.

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Artemis IV	Orion Gateway HLS	• S-band (Orion and HLS) • X-band (Gateway) • Ka-band (HLS and Gateway)
Artemis V	Orion Gateway HLS	• S-band (Orion and HLS) • X-band (Gateway) • Ka-band (HLS and Gateway)

DSN will provide critical support for the Artemis program across multiple campaigns (Artemis I, II, III, etc.) for multiple vehicles including Gateway/PPE and Orion and has a critical role to play in the near-term before new Lunar Exploration Ground Segment (LEGS) assets are deployed. LEGS will provide "18-m class" performance (or better) apertures and/or associated commercial services at multiple distributed ground sites to provide continuous lunar coverage. LEGS is intended to alleviate, but not entirely offset, lunar demand on the DSN, allowing the DSN to concentrate resources on deep space users. The next section will provide an overview of DSN lunar capabilities and discuss requirements levied on the network by the lunar missions.

4. Addressing Challenges in DSN to Meet Lunar Need

With the return to the moon stressing the capacity of the DSN along with the full portfolio of other DSN mission users, the DSN identified high-level requirements for the DLEU task to address uplink, downlink, and data delivery functions, which are discussed below.

4.1 Near Earth K-Band Uplink

The DSN was designed to support deep-space Ka-band capability. To support lunar missions, which are in near space, DLEU will add a new K-band[†] uplink and a K-band exciter at two Beam Waveguide (BWG) antennas in each complex, as well as new mirrors to reflect or pass new frequencies. The ability to transmit and receive simultaneously at multiple radiofrequency (RF) bands is a functional need for antennas in the DSN. The DLEU upgrades are targeting simultaneous uplink capabilities in either near-Earth K-Band and S-Band or K-Band and X-Band (K-Band + S-Band or K-Band + X-Band). DLEU added 250W transmitters with near Earth K-band (22.5 GHz) uplink to antennas DSS-26 (GDSCC) and DSS-36 (CDSCC) along with near Earth K-band (26GHz) downlink and will provide the same uplink upgrade to antennas which already have near Earth K-band downlink capability: DSS-24 (GDSCC), DSS-56 (MDSCC), DSS-34 (CDSCC), and DSS-54 (MDSCC). DLEU will also add this capability to the test facilities DTF-21, CTT-22, and MIL-71.

In addition, adjustments to the configuration of the dichroic mirrors must be completed to handle the new frequency band. Dichroic mirrors reflect or pass RF energy depending on the frequency. Introduction of a new frequency band fundamentally affects the arrangement of dichroic mirrors directing signal from (and to) the antenna feed. As shown in Figure 2, for the DSN 34m BWG antennas, modifications will be made to the configuration of the M6 and M7 mirror assemblies. In the M6 position, a pair of interchangeable dichroic reflectors are mounted: M6 and M6A. The M6 mirror (S/X – Band) requires no modification, while the M6A mirror must be redesigned to allow 22.5 GHz K-band uplink, in addition to the existing 26 GHz K-band downlink, to pass. In the M7 assembly, a new M7A reflector is being designed to reflect X-Band and allow 22.5 GHz and 26 GHz to pass. The mounting rails holding each pair of mirrors (M6 / M6A and M7 / M7A) must be lengthened to ensure that the mirrors can be fully interchangeable at each position. A K-band uplink junction also must be designed and added to the 26 GHz K-band downlink microwave subsystem to support the 22.5 GHz K-band uplink. These new components and reflector assembly changes are shown in Figure 3.

[†] The DLEU task refers to this uplink as a K-band to distinguish near space Ka-band frequency from the deep space Ka-band frequency. For Artemis lunar activities, DLEU will implement capabilities that operate in the following direct to Earth (DTE) frequency bands listed in SFCG Recommendation 32-2R4 [6]:

- S-band: 2025-2110 MHz (uplink), 2200-2290 MHz (downlink)
- X-band: 7190-7235 MHz (uplink), 8450-8500 MHz (downlink)
- K-band: 22.55-23.15 GHz (uplink), 25.5-27.0 GHz (downlink)

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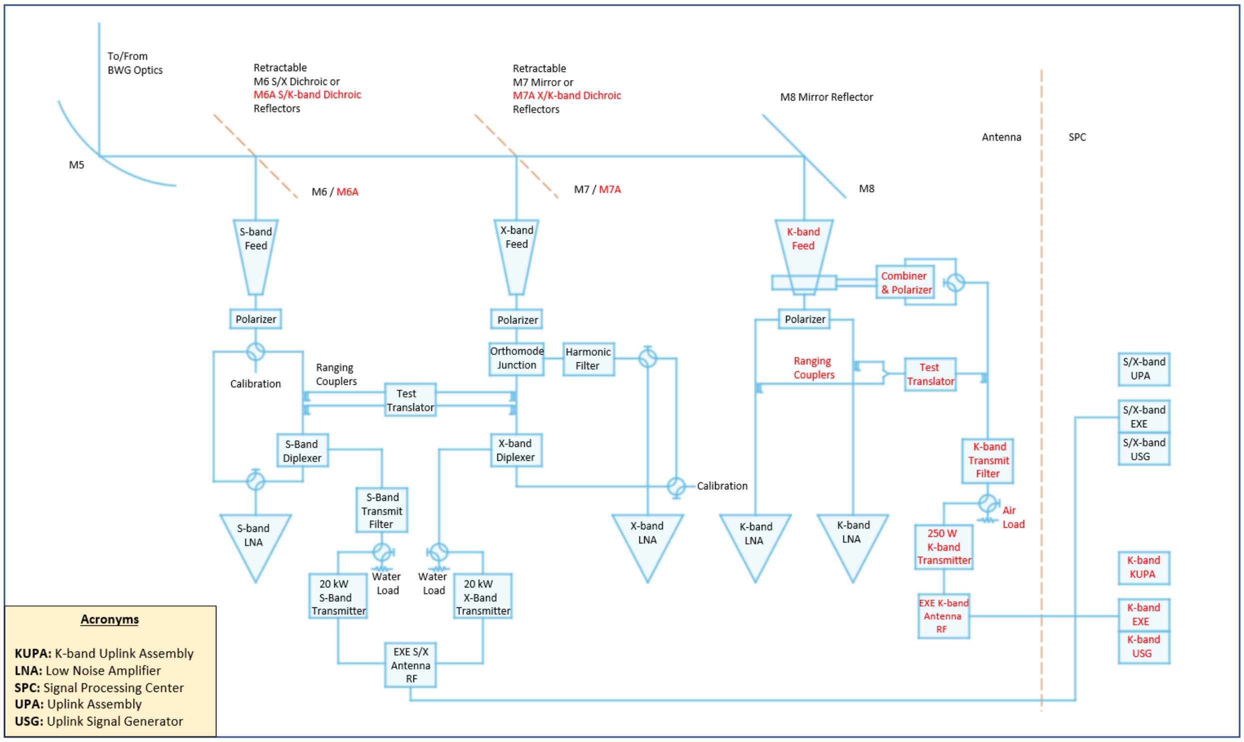

Figure 2: Dichroic Mirror Schematic

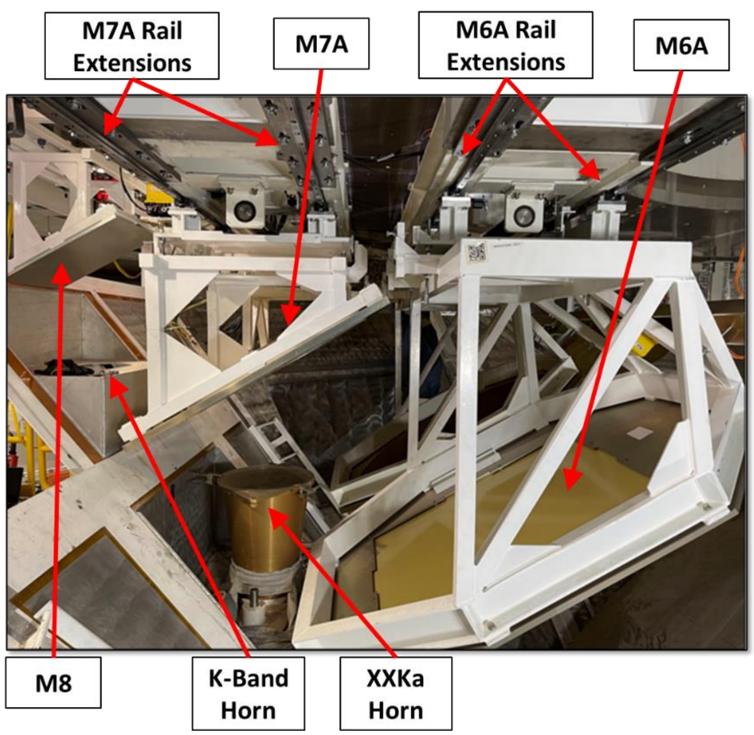

Figure 3: Upgraded Dichroic Reflector Assembly

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The data rate capability will increase to 20 Mbps (coded) for K-band and 10 Mbps (coded) for X-band. The uplink signal is generated by the exciter, which creates the carrier, including any phase continuous carrier frequency ramping, modulates the uplink data provided by the mission onto the carrier, generates and modulates the ranging signal onto the carrier, if needed, and then upconverts the signal to the desired frequency band. Exciter modulation capability is common for all DSN exciters, so 20 Mbps data rate will be available at all bands; however, spectrum constraints may not allow full usage at all bands.

DLEU will also add capability for QPSK and OQPSK modulation, along with filtered QPSK and OQPSK and filtered Binary Phase Shift Keying (BPSK) modulation to reduce phase changes and use less bandwidth. The design effort must take into account that, due to the range of age of the antennas (the span of antennas, from oldest to newest, is twenty-eight years), there are three different antenna configurations (servo type and equipment platform combinations) that require specialized considerations for the different equipment configuration and interfaces.

4.2 Downlink Processing of High Rate LDPC Coding

To support the required high telemetry data rates of lunar missions, downlink processing of High Rate Low Density Parity Check (LDPC) decoding is currently in-test, with an expected delivery of February 2023. This upgrade adds 150 Mbps LDPC decoding to the High Rate Common Platform (HRCP) receiver that is currently used for tracking K-band missions such as Transiting Exoplanet Survey Satellite (TESS). The Consultative Committee for Space Data Systems (CCSDS) defines a set of LDPC codes for use in space applications. Each antenna’s signal can be routed to the HRCP, which currently performs 300 Megasymbols per second (Msps) symbol tracking and 150 Megabits per second (Mbps) Convolutional / Reed-Solomon decoding. Integrating the LDPC decoding does not affect the symbol loop, or the frame delivery to the data transport, since the bit and symbol rates and frame sizes are within its existing requirements. This upgrade also requires additional Field Programmable Gate Array (FPGA) boards to house the LDPC decoder elements, which allow multiple decoder blocks to operate in parallel.

As part of this upgrade, DLEU will provide two channels for each antenna with near Earth K-band downlink, for a total of four channels per complex. Test signal capability upgrade is also included.

4.3 High Rate Low Latency Data Delivery

Supporting operations at the moon, particularly human missions, creates a different demand and expectation for service compared to deep space robotics. The lunar campaign requires lower latency data delivery and higher rate downlink. Providing 150 Mbps to aggregate timely low latency data delivery is more than a factor of ten increase in the current system’s requirements and capability; the upgrade to high rate low latency data delivery needs to handle the complex overlap period when spacecraft are in view and tracked by two sites. This upgrade requires modifications to the Data Capture and Delivery (DCD) subsystem, along with adjustments to other data handling subsystems such as the Space Link Extension (SLE) Gateway (where all DSN missions bind to get their telemetry data), allowing for faster data processing with less latency. Additionally, the WANs between the complex and JPL will have their bandwidth increased by 200 Mbps to support the delivery of the higher data rates. Planning for this upgrade assumes that the high rate streams (> 1 Mbps) will use the large frames (16k bits), and that spacecraft will use Virtual Channels to separate low latency and high latency data.

4.4 Current Status

To minimize the impact to the mission community that would occur with 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 calendar year 2022 and work on DSS-24 began in January 2023.

5. Conclusion

SCaN is committed to understanding future mission requirements and demand to make informed decisions about network improvements. To support new lunar missions, DSN is making upgrades which support higher data rates and faster data delivery. 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.

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References

[1] C. Chang, S. Slobin, DSN Telecommunications Link Design Handbook, 03 July 2018, https://deepspace.jpl.nasa.gov/dsndocs/810-005/Binder/810-005_Binder_Change44.pdf (accessed 18.12.22)
[2] J. B. Berner, "Deep Space Network in the CubeSat Era," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 34, no. 4, pp. 46-54, 1 April 2019
[3] D. Shin, Deep Space Network Frequency and Channel Assignments, 19 April 2022, https://deepspace.jpl.nasa.gov/dsndocs/810-005/201/201F.pdf (accessed 14.11.22)
[4] B. Dunbar, NASA's Exploration Campaign: Back to the Moon and on to Mars, 16 April 2018, https://www.nasa.gov/feature/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars (accessed 18.12.22)
[5] K. Mars, Gateway, 17 November 2022, https://www.nasa.gov/gateway/overview (accessed 18.12.22)
[6] Space Frequency Coordination Group, Recommendation SFCG 32-2R4: Communication and Positioning, Navigation, and Timing Frequency Allocations and Sharing in the Lunar Region, 27 July 2022, https://www.sfcgonline.org/Recommendations/REC%20SFCG%2032-2R4%20(Freqs%20for%20Lunar%20Region).pdf (accessed 14.12.22)