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Deep Space Station 17: A University-Operated Affiliated Node on the NASA Deep Space Network and the Lunar Tracking Network

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Abstract

The world-wide space community has a renewed interest in the Moon. NASA will launch humans to the Moon again with the Artemis program, that had its first launch in 2022. ESA has concepts for heavy lift lunar rockets and a Moon Village, and China National Space Agency (CNSA) has the Chang'e program, a series of robotic missions with a goal toward human landing and the establishment of a research station at the Moon's south pole. NASA's Gateway and Commercial Lunar Payload Services (CLPS) programs are in development. Meanwhile, a new era of Solar System exploration began in 2018 with the launch of the twin Mars Cube One (MarCO) CubeSats. CubeSats are being planned for lunar and interplanetary research, with 10 CubeSats flown on NASA's Artemis 1 mission in 2022. The success of MarCO and Artemis 1 will no doubt open the door for CubeSat and smallsat exploration of the solar system. All of these activities will require ground support for communications, navigation and tracking-support that requires significant infrastructure including ground stations with large apertures, full-motion antennas and specialized deep space ranging and telecommunication instrumentation. The CubeSat explorers, especially, require sensitive, large aperture ground stations to close communications links. Government based deep space networks (i.e. NASA's DSN) are generally considered to be heavily subscribed with the current non-Cubesat mission set, and, even with the expansion of the new antennas planned and with the implementation of new techniques (i.e. multiple spacecraft per aperture), will be challenged accommodate the large number of missions expected as the lunar and smallsat revolutions unfold. To begin to address this challenge, partnership between JPL and Morehead State University (Kentucky, U.S.A.) was initiated in 2014 to develop a strategy to enhance DSN capabilities by utilizing existing non-NASA assets (i.e. university and non-profit radio astronomy observatories). An enhanced DSN can be achieved by transferring DSN processes and techniques, precision timing standards, data formatting, handling and transfer protocol, and mission and ground operation processes to existing university-based large aperture antennas. The team used the Morehead State University 21 m Space Tracking Antenna as a case-study to prove the validity of the concept of adding non-NASA nodes to the DSN. The goal of this project has been to develop and implement a strategy to transfer DSN processes and protocol to the MSU 21 m antenna system to enable integration into the DSN as an auxiliary station to support small-sat missions. The program focused on the implementation of DSN capabilities with deep space communication and navigation tracking techniques, including Space-link Extension (SLE) protocol and CCSDS data standards, and asset scheduling capabilities. The 21 m antenna system has been upgraded for DSN-compatibility and the station, designated DSS-17, had its first operational mission (CAPSTONE) in July 2022.

DSS-17 is also serving as a pilot ground station for three emerging technologies with the potential to substantially lower CubeSat mission cost and risk, or even enable new types of deep space missions to be proposed. These new capabilities include Disruption Tolerant Networking (DTN), spacecraft-initiated operations utilizing a beacon tone service, and Opportunistic Multiple Spacecraft per Aperture (OMSPA). DTN and beacon operations capabilities have been implemented on DSS-17. These capabilities will be validated for operational use at DSS-17 in the future.

Additionally, DSS-17 has been incorporated into the Intuitive Machines, LLC. (IM) Lunar TT&C Network (LTN) that has been established to support IM-1, a commercial lunar lander supported by NASA under the Commercial Lunar Payload Services (CLPS) program, and to meet future lunar mission requirements. The LTN utilizes existing large aperture stations including Morehead State University's 21 meter station (USA), Goonhilly's 32 meter Earth Station (UK), the CSIRO Parkes Observatory 64 meter radio telescope (Australia), JAXA's 18 meter tracking station in Okinawa (Japan), and a 12 meter uplink and 26 meter downlink stations of SANSA and the Hartebeesthoek Radio Astronomy Observatory (South Africa). These stations operate for the LTN in the deep space S-band and X-bands. An overview of the DSS-17 upgrade, including measured performance characteristics and the commercial LTN will be discussed.

Acronyms/Abbreviations

Consultative Committee for Space Data Systems (CCSDS), Commercial Lunar Payload Services (CLPS), Deep Space Network (DSN), Deep Space Station (DSS), Disruption Tolerant Networking (DTN), Intuitive Machines (IM), Jet Propulsion Laboratory (JPL), Lunar Tracking Network (LTN), Lunar Data Network (LDN), Multiple Spacecraft per Aperture (MSPA), Opportunistic Multiple Spacecraft per Aperture (OMSPA), Space Link Extension (SLE)

1. Introduction

The space exploration community has a renewed interest in the Moon, not only as a stepping stone to Mars, but for its own inherent value. This interest will ultimately culminate in the first commercial landers on the Moon, a variety of rovers, hoppers and stationary assets, a human return to the Moon (Artemis 3) and ultimately a lunar base. The Moon has become "cool again", a phenomena that has been referred to as the retro lunar moment.[1] Renewed interest in the Moon has led to a sort of modern space race to return to the lunar surface. In 2019, the Chinese landed Chang'e-4, a small lander and rover, becoming the first ever to land of the far side of the Moon. India attempted to land Chandrayaan-2 in 2019; while it orbited the Moon successfully, it's landing was unsuccessful. An Israeli non-profit, Space IL tried to send a robotic lander also in 2019, meeting the same fate. The NASA Commercial Lunar Payload Services (CLPS) will deliver payloads to the lunar surface by utilizing commercially-produced launch vehicles, landers, and orbiters that will test technologies and demonstrate capabilities to assist NASA in exploring the Moon and prepare for human missions.

The benefits of lunar exploration have led to a revitalization of lunar exploration initiatives and, indeed, to a new space race. The major space-faring nations have ambitious plans. China is taking an ambitious but step-wise approach, and foresees Taikonauts landing in the lunar surface by 2030. The European Space Agency introduced the concept of an international "moon village" envisioned in the 2050 time-frame. Russia has also described plans for sending Cosmonauts to the moon by 2030. India, Israel, and the United Arab Emirates all have lunar aspirations. For NASA, the moon is considered a stepping stone to Mars. NASA's Artemis program is well-underway with Artemis I flown and Artemis II and III in development. Artemis III will achieve a major milestone with the next human landing. [2] This renewed interest in the Moon has led to a modern space race to return to the lunar surface, this time between the U.S. and China. NASA Administrator, Bill Nelson, has referenced the new space race with respect to the CNSA stated a goal of landing Taikonauts on the Moon by 2030.[3]

All of these initiatives will require ground support in the form of telemetry, tracking and control services. Telemetry and Command services, while non-trivial to implement for lunar distances, involve relatively available commercial technologies. Services for tracking- ranging and precision Doppler measurements that are required for deep space/lunar navigation, however, are more complicated and challenging to implement. New ground station assets that will need to be established to support these initiatives will have to have all three. This paper describes a test-case in which these capabilities were implemented on an existing radio telescope/LEO ground station, and how, as an independently-owned station, DSS-17 provides services for both NASA and the commercial space sector.

2. DSS-17

The 21-m Space Tracking Antenna at MSU was brought on-line in 2007 as a radio telescope and research tool for students, and also to provides satellite tracking, telemetry and control services to other universities, private aerospace clients and government agencies. The full-motion, 21-meter parabolic dish antenna system serves as an Earth station for satellite mission support and also acts as a test bed for advanced radio frequency systems. The system is capable of tracking fast-moving, low-transmitting power small satellites in low Earth orbit as well as satellites at geostationary, lunar and potentially Earth-Sun Lagrangian orbits. In 2021, the 21-m Space Tracking Antenna was upgraded and approved as an affiliated Node on NASA's Deep Space Network (DSN), and is now designated NASA DSS-17.[4]

The 21-m reflector has good surface accuracy (0.0166" root mean square (RMS)) and tracking accuracies (0.005° RMS at Ku-Band), and excellent pointing (<= 0.01° RMS). These characteristics support satellite tracking services from L-band to Ku-band. Currently operational bands, for which RF systems are in place, include L-band, S-band and X-band. RF and IF systems are a combination of custom-in-house developed hardware and COTS systems. RF feeds are developed in-house with some elements professionally produced. S-band and X-band are the primary service bands, with the highest performing feed system being X-band that has been developed for lunar and deep space mission profiles. The frequency ranges for S-band and X-band are shown below in Table 1.[5]

Table 1 21 M Antenna System Radio Frequency Operating Regimes*

Band Designation	Deep Space Bands		Near Earth Bands	
	Uplink (MHz)	Downlink (MHz)	Uplink (MHz)	Downlink (MHz)
S-band	2110-2120	2290-2300	2025-2110	2200-2290
X-band	7145-7190	8400-8450	7190-7235	8450-8500

*Frequency bands listed are ranges in which the 21 m system has capabilities, not for which the system is licensed. Note that all missions must acquire an FCC/NTIA license or license from their governing organization along with spectrum coordination (with IARU) for both the spacecraft and the ground station

To support deep space navigation services, a Hydrogen MASER time and frequency standard has been implemented along with a frequency distribution system. The Hydrogen MASER is disciplined for long-term drift with a GPS standard. This frequency standard system facilitates precision ranging and Doppler measurements. The MASER implementation utilizes a Microchip MHM-2020 Active Hydrogen MASER and a Monitor and Control System developed in house. The MASER timing signal is distributed to all of the relevant systems of DSS-17 and the Mission Operations Center. The MASER provides 10 MHz Signal to Master Clock Assembly and a 100 MHz to the system converters. All MASER parameters, and indeed all major systems are monitored and controlled via the Station Monitor and Control System (SMC) that is interfaced via Ethernet.

A summary of the overall empirically measured validation testing results are shown below in Table 2 that provides an overview of the primary performance aspects of the ground station. These values are utilized by potential users of DSS-17 in communications link models to determine the suitability of DSS-17 for their mission profile.[6]

Table 2 DSS-17 Performance Metrics

Performance Measure	Performance Value
X-band Uplink Range	7.145 – 7.235 GHz
X-band Downlink Range	8.350 – 8.500 GHz
LNA Temperature	20 K
System Temperature Tsys	90 K
Antenna Gain	62.7 dBi (@8.4 GHz)
G/T at 5° Elevation	42.0 dBi/K
Time Standard	H- MASER (1ns/day)
EIRP	91.4 dBW (nominal)
HPBW	0.1150 deg
SLE Compliant	Yes
CCSDS Capable	Yes
Forward Error Coding	Reed Solomon/Convolutional, Turbo, Low Density Parity Check
Radiometric	Angle, Doppler, Sequential Tone and PN Ranging (2-Way and 3-Way)
Ranging Precision	+/-1 range unit (0.94 ns) 1 m (1 sigma Accuracy)

Figure 1 The 21 m Deep Space Tracking Antenna at Morehead State University, designated NASA DSS-17

DSS-17 can be used in several modes: 1.) as an affiliated NASA Deep Space Network node, 2.) as a node on the Intuitive Machines Lunar Tracking Network, 3.) as an independent single-aperture station for lunar and interplanetary TT&C services, 4.) as a beacon polling station for deep space missions, 5.) as an experimental station for techniques to be implemented in the future including MSPA and DTN.[7] Modes 1 and 2 are the focus of this paper and are discussed in the following sections.

3. Enhancing the DSN

3.1 The DSN

The NASA Deep Space Network is the communications assets that connects mission operation teams with their spacecrafts to conduct scientific investigations throughout the solar system. The DSN is composed of three major tracking complexes – Goldstone in California, United States; Canberra, Australia; and Madrid, Spain. These sites are evenly spread across the globe to ensure constant visibility with spacecraft. As of 2023, there are 14 operational antennas in the network – three 70-m and eleven 34-m antennas. Telemetry and tracking data from spacecraft are captured at the three complexes, and routed to the Deep Space Operation Center at the Jet Propulsion laboratory, Pasadena, California to be delivered to the mission users. Conversely, command data flown from mission control centers to the complexes to be radiated to their respective spacecraft. The DSN currently supports 35+ missions.

3.2 Expanding the DSN

Having additional antenna assets would enhance the DSN capability to serve ever larger mission set. DSS-17, situated in Kentucky between Madrid and Goldstone, can offset the loading demand on the DSN at those two sites. Besides the normal load sharing, DSS-17 can also serve as additional resource to be scheduled when there is a spacecraft emergency that prompts unexpected critical need to maintain contact with spacecraft.

What made the integration of DSS-17 into the DSN relatively simple is that the interfaces between DSS-17 and mission users are the same as with any other DSN antennas. DSS-17 operations rely on the common DSN infrastructure such as antenna scheduling, predicts generation for antenna pointing, Doppler frequencies, spacecraft telecommunication configuration, telemetry and tracking data delivery. As such, DSS-17 interfaces to mission operations systems/teams are the same, regardless whether the track is done on the DSN antenna or DSS-17. This high degree integration is achieved by having the backend digital signal processing equipment at Morehead to be the same as in other DSN antennas.

DSN expanded services have, in the past, been provided by ESA stations, JAXA stations and others through Cross-Support Agreements. The concept of Affiliated Stations, however, is new and is still being defined. However, a role for DSS-17 has been defined as providing:

- Telemetry, Tracking and Control Services for Lunar and Interplanetary (Inner Solar System) CubeSats
- Emergency Services for a Variety of Mission Profiles
- Experimental technologies that can be investigated without taking an operational asset off-line or using DSS-13. Long-term experiments are possible

DSS-17 and the concept of an Affiliated DSN node has, to date, been successful in its goal of reducing the loading on the DSN created by the new wave of lunar CubeSats.

4. The Intuitive Machines Lunar Tracking Network (LTN)

The U.S.-based aerospace company, Intuitive Machines (IM), established the IM Lunar Tracking Network (LTN) initially to service its own payloads and others of the Commercial Lunar Payload Services (CLPS) initiative. This network of independently owned and operated large-aperture ground stations was establishment in 2021 by IM under contractual and teaming agreements with each station. The LTN is the world's first commercial deep space network to exist and has great possibilities to service lunar missions and beyond, utilizing some of the largest and most reliable ground stations in existence.

4.1 CLPS Overview

NASA established the Commercial Lunar Payload Services (CLPS) initiative [8] to pave the way for upcoming Artemis missions by delivering science and technology demonstration payloads to the lunar surface. Through this initiative, companies bid on payload delivery. As part of the contract, the awardees are responsible for payload integration and operations, as well as launch from Earth and landing on the Moon. Intuitive Machines' initial missions will be carried out by the Nova-C lander, launched atop a SpaceX Falcon 9 rocket [9].

4.2 LTN Overview

To support communication with the Nova-C lander, Intuitive Machines established the Lunar Tracking Network (LTN). The goal was to obtain data services at lunar distance without going through NASA's highly subscribed DSN. To achieve this, IM partnered with commercial and radio astronomy ground station providers around the world. Each site has a "half rack" of IM equipment to provide the necessary interface to the antenna, along with network infrastructure to return the data to Nova Control (or conversely, send commands from Nova Control to the Nova-C lander). Capabilities are also built-in to allow encrypted direct access from a customer's facility to data and telemetry/command from payloads onboard Nova-C during transit and surface-based operations. The LTN is built to be compliant with NASA's LunaNet and also includes a planned data relay satellite constellation. The first satellite is slated to launch as a rideshare with the IM-2 mission.

Since 2020, Intuitive Machines (IM) has been developing the Lunar Tracking Network (LTN) that incorporates ground stations in the USA, England, Australia and South Africa. The geographic distribution of the LTN stations is global, with stations on every habitable continent (Figure 2). Effectively, IM has some of the largest ground stations in the world committed as partners in the LTN. Many of these instruments were designed and operated as radio telescopes and therefore have large apertures, extreme sensitivity and state-of-the-art receiver and transmitter technologies.

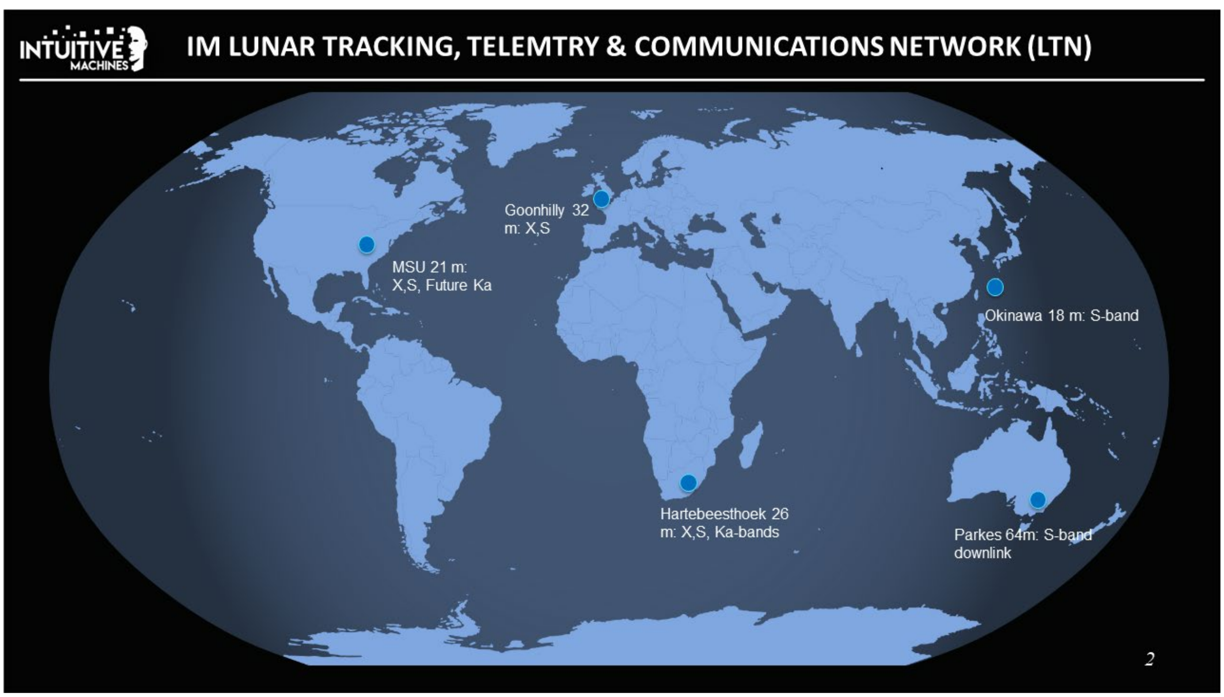
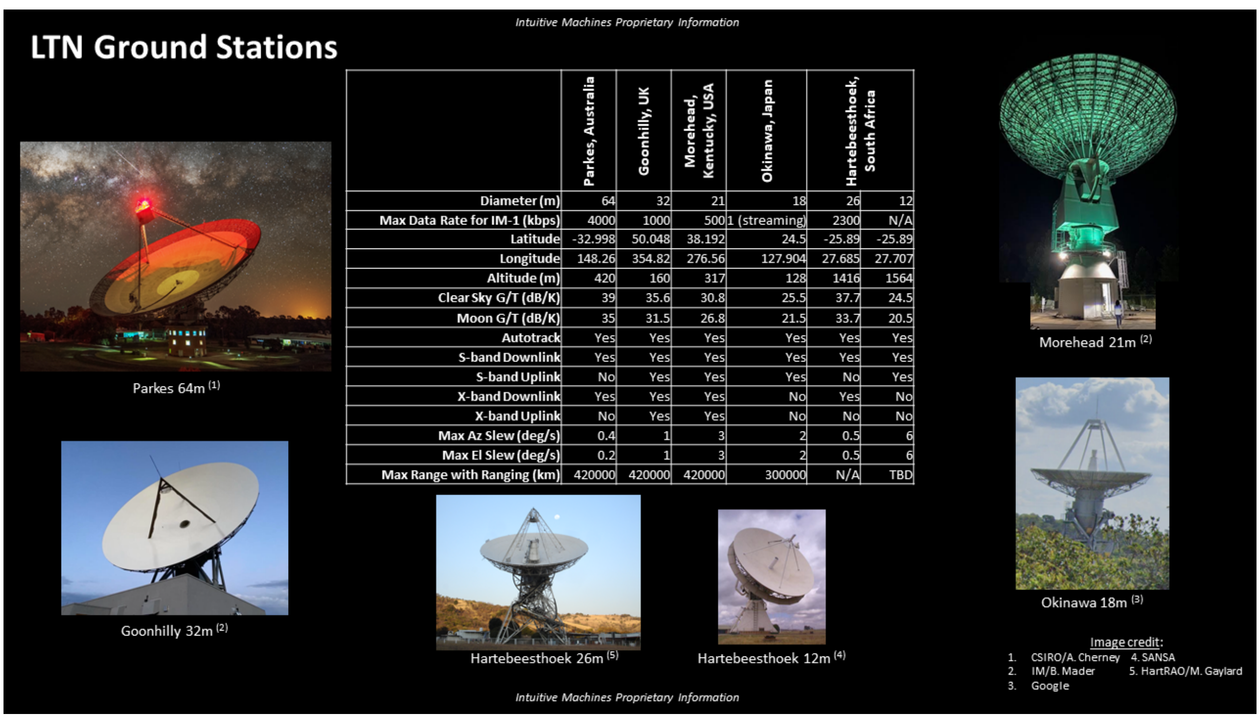


Figure 2 Intuitive Machine's Lunar Tracking Network (LTN) is the first commercial lunar and deep space networks and has some of the world's largest ground stations

There are numerous benefits of the LTN as it exists today. Primary among these are:

1.) The LTN is comprised of some of the largest, most sensitive apertures in existence
2.) The LTN stations are individually owned and operated and may provide services for their respective civilian space programs
3.) The LTN has global coverage with both Northern and Southern hemispheres represented (needed for navigation and trajectory modeling)
4.) The LTN is comprised of proven stations with experience in ground support of deep space mission
5.) The LTN elements have existing infrastructure for connectivity, scheduling and operations
6.) The LTN stations are operated by organizations with significant experience in Ground Operations and instrumentation development, facilitating potential evolution of the elements as new technology is available
7.) The LTN has a common transmitter/receiver system- IM's back-end architecture that is easily installed, tested and upgraded at each station, requiring only an IF input, power, connectivity and security

Figure 5 Intuitive Machines half rack on-location at an LTN ground station. All stations have a common transmit/receive system



	Parkes, Australia	Goonhilly, UK	Morehead, Kentucky, USA	Okinawa, Japan	Hartebeesthoek, South Africa	
Diameter (m)	64	32	21	18	26	12
Max Data Rate for IM-1 (kbps)	4000	1000	500	1 (streaming)	2300	N/A
Latitude	-32.998	50.048	38.192	24.5	-25.89	-25.89
Longitude	148.26	354.82	276.56	127.904	27.685	27.707
Altitude (m)	420	160	317	128	1416	1564
Clear Sky G/T (dB/K)	39	35.6	30.8	25.5	37.7	24.5
Moon G/T (dB/K)	35	31.5	26.8	21.5	33.7	20.5
Autotrack	Yes	Yes	Yes	Yes	Yes	Yes
S-band Downlink	Yes	Yes	Yes	Yes	Yes	Yes
S-band Uplink	No	Yes	Yes	Yes	No	Yes
X-band Downlink	Yes	Yes	Yes	No	Yes	No
X-band Uplink	No	Yes	Yes	No	No	No
Max Az Slew (deg/s)	0.4	1	3	2	0.5	6
Max El Slew (deg/s)	0.2	1	3	2	0.5	6
Max Range with Ranging (km)	420000	420000	420000	300000	N/A	TBD

Figure 3 LTN Station Performance Specifications

4.3 Nova Control

Nova Control is Intuitive Machines' lunar operations center, where IM personnel coordinate LTN operations, and will operate the Nova-C lander and IM's planned Lunar Data Network (LDN) lunar relay constellation. This state-of-the-art facility is built in a circular fashion, in a departure from the traditional "rank-and-file" rows of a typical control center. This side-by-side configuration allows for enhanced collaboration, as operators can easily talk to their neighbor, or the entire team can turn and face the center table for discussions. Nova Control has been validated using the LTN to communicate with NASA's Lunar Reconnaissance Orbiter (LRO), in addition to tracking Orion as part of the Artemis I mission. These tests proved the real-time end-to-end data flow and voice traffic between the LTN ground stations and Nova Control, in addition to Intuitive Machines' capabilities in providing scheduling and tracking information prior to the event.

Figure 5 Intuitive Machines Nova Control

5. Operational and Experimental Services

DSS-17 is now providing operational services for NASA and missions launched and managed by the private sector, along with experimental services for NASA, JPL, Johns Hopkins Applied Physics Laboratory, and Morehead State University. These services are briefly described in the following sections.

5.1 Operational Services

All activities associated with operating DSS-17 as a DSN node, are managed by Morehead State University personnel and supported by a JPL-DSN engineering team. Activities associated with operating DSS-17 for the IM Lunar Tracing Network and scheduled by Intuitive Machines. Activities associated with commercial space services are managed also by Morehead State University. The philosophy behind DSS-17 operations is to provide cost-effective deep space services, primarily for CubeSats. DSS-17, being a university-based station, utilizes personnel and students at Morehead State as the Operational Staff. DSS-17 operates in a single band at a time (X-band or S-band) and has a much simpler network monitor and control system, providing adequate, but limited meta data on the station during a track. Additionally, DSS-17 does not have the depth of back-up systems that a typical DSN station has. While the inventory of critical spares is constantly being expanded, there are several single points of failure that make the use of DSS-17 higher risk than typical NASA DSN stations. However, this risk is mitigated by the fact that DSS-17 serves as a node in two networks, DSN and LTN, that have alternative stations that can be scheduled in the case of a ground station anomaly.[10]

As a DSN node, DSS-17 has been added to the NASA network (NASA Mission Backbone) to allow the 21 m to serve as a functional node on the DSN. The current mission support set for DSS-17 includes CAPSTONE and several of the Artemis 1 CubeSats including: Lunar IceCube, LunaH-Map, NEAScout and CuSP. Details of these support activities are provided in Table 5 below:[11]

Table 2 DSS-17 Support of Artemis 1 CubeSats

Spacecraft	Downlink Band	Uplink Band	Ranging	Doppler	Near-Earth* or Deep-Space U/L
HMAP	X	X	Y	Y	Near-Earth
LFL	X	X	Y	Y	Near-Earth
MLIC	X	X	1	Y	Near-Earth
NEAS	X	X	D/L only	D/L only	Deep-Space
CuSP	X	X	D/L only	D/L only	Deep-Space
CAPSTONE	X	X	Y	Y	Near-Earth
LRO	S	S	U/L only	U/L only	IM-1
IM-1	S	S	Y	Y	
	Near-Earth X-Band U/L: 7.145 GHz – 7.190 GHz Near- Earth X-Band: D/L Band: 8.450 – 8.500 GHz Near Earth S-Band U/L: 2.025 – 2.110 GHz Near Earth S-Band D/L: 2.200 – 2.290 GHz			Deep Space X-Band: U/L: 7.145 – 7.190 GHz Deep Space X-Band D/L: 8.400 – 8.450 GHz Deep Space S-Band: U/L: 2.110 – 2.120 GHz Deep Space X-Band D/L: 2.290 – 2.300 GHz	

DSS-17 became effectively operational with the launch of CAPSTONE in June 2022.[12] Shortly after,10 Artemis 1 CubeSat missions were launched in November 2022. DSS-17 provided TT&C and emergency services to the Artemis I CubeSats during late 2022-2023. Additionally, the 21 m station continues support for S-band missions when time is available, i.e. during times that are not devoted to the primary mission of X-band deep space operations. The 21 m is operated at X-band either as DSN affiliated node DSS-17 on the NASA Mission Backbone as a DSN station (scheduled through the DSN Commitments and Scheduling Office for NASA missions) or as an independent station for NASA and non-NASA missions. At S-band, the current configuration supports operations as an independent station offering direct connection from the mission's operation center (MOC) to the 21 m Station Operations Center (SOC). The S-band system is primarily used for lunar missions (LRO instrument support and IM-1 lander). S-band support is scheduled by Morehead State University, while X-band support is primarily scheduled through the NASA Deep Space Network.

5.2 Experimental Services

In addition to providing operational deep space services, DSS-17 is also serving as a pilot ground station for three emerging technologies with the potential to substantially lower CubeSat mission cost and risk, or even enable new types of deep space missions to be proposed. These new capabilities include Disruption Tolerant Networking (DTN), spacecraft-initiated operations utilizing a beacon tone service, and Opportunistic Multiple Spacecraft per Aperture (OMSPA). DTN and beacon operations will be flight validated for use on CubeSats by the Lunar IceCube mission, which will also certify these capabilities for operational use at DSS-17.

One such capability is known as beacon operations, has been an operational service within NASA for over a decade but with very limited use. With this capability, the spacecraft can determine when tracking for telemetry is needed and uses the beacon tone to indicate the urgency of ground response. New Horizons has used beacon monitoring very successfully for years to lower the cost of cruise during "hibernation" periods and to reduce the loading on the Deep Space Network. MSU's DSS-17 ground station enables a large number of future missions to use this technique for any or all mission phases to decrease mission risk, enable coordinated science with other platforms, and decrease loading of the DSN. The reason why DSS-17 is key to widespread adoption is that it slews much faster than DSN antennas and as such can poll several spacecraft per hour, potentially informing missions much more frequently than with scheduled telemetry passes that their spacecraft is healthy. Or, if an anomaly occurs, ground intervention can occur much sooner than would have occurred otherwise. What mission manager wouldn't want to know everyday that their spacecraft is healthy when otherwise, they would have to wait perhaps several days or a week or more for this information via a scheduled pass. The beacon tone can also be mapped to a particular spacecraft state that can inform the ground operations team what to do during the next scheduled pass. Either use of the tone system can offer substantial advantages to small spacecraft missions that are inherently lower priority compared to flagship NASA missions when competing for aperture time.

Another pilot capability is Disruption Tolerant Networking (DTN). Disruption Tolerant Networking (DTN) is a protocol suite that extends the terrestrial Internet capabilities into highly stressed data communication environments where the conventional Internet does not work well. These environments are typically subject to frequent disruptions, unidirectional links, possibly long delays and high error rates. For comparison, in the internet, each received packet is forwarded immediately, if possible, and deleted if immediate forwarding is not possible. In a Space Network, each received packet is forwarded immediately, if possible, stored for future transmission if forwarding is not currently possible but is expected in the future. DTN is especially timely for small spacecraft because it is becoming part of the core architecture for lunar exploration and can enable constellations of spacecraft and coordinated observations among small spacecraft.[13] Also, since CubeSat communications will generally be lower priority and may more disrupted/uncertain than for NASA's larger missions, DTN can add robustness to operations concepts and can thus be viewed as a risk reduction measure. Additionally, DTN is core capability of NASA's LunaNet and IM's Lunar Data Network services and architecture.

6. Conclusions

Lunar exploration has been revitalized with a significant number of lunar assets, landers, orbiters, rovers, hoppers, outpost stations, human exploration and orbiting stations that have occurred or are in development. Lunar initiatives like CLPS, Gateway, Artemis, Change, Chandrayan and others are in full swing. Small satellite platforms, in particular CubeSats are presenting a new paradigm for lunar and inner solar system exploration. All of these activities require large aperture ground stations that are capable of not only providing command and telemetry services, but precise ranging and Doppler measurements for navigation support. A new model, that of utilizing existing radio telescopes and/or upgrading LEO stations for lunar and deep space services, is being explored. Successes have been achieved with a case-study, NASA's Deep Space Station 17, which has validated the concept of upgrading a university (or commercially-based) existing ground station to provide deep space services. Upgrading existing stations is much more cost effective than building new 30 meter-class assets (at X-band or S-band), or 12-18 meter-class assets at Ka-band, which is extraordinarily expensive and time-consuming. More of these upgrades will be required to support the thriving lunar ecosystem in the near future.

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