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Lunar and Lagrangian Point L1/L2 CubeSat Communication and Navigation Considerations

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ABSTRACT

CubeSats have grown in sophistication to the point that relatively low-cost mission solutions could be undertaken for planetary exploration. There are unique considerations for lunar and L1/L2 CubeSat communication and navigation compared with low earth orbit CubeSats. This paper explores those considerations as they relate to the Lunar IceCube Mission. The Lunar IceCube is a CubeSat mission led by Morehead State University with participation from NASA Goddard Space Flight Center, Jet Propulsion Laboratory, the Busek Company and Vermont Tech. It will search for surface water ice and other resources from a high inclination lunar orbit. Lunar IceCube is one of a select group of CubeSats designed to explore beyond low-earth orbit that will fly on NASA's Space Launch System (SLS) as secondary payloads for Exploration Mission (EM) 1. Lunar IceCube and the EM-1 CubeSats will lay the groundwork for future lunar and L1/L2 CubeSat missions. This paper discusses communication and navigation needs for the Lunar IceCube mission and navigation and radiation tolerance requirements related to lunar and L1/L2 orbits. Potential CubeSat radios and antennas for such missions are investigated and compared. Ground station coverage, link analysis, and ground station solutions are also discussed. This paper will describe modifications in process for the Morehead ground station, as well as further enhancements of the Morehead ground station and NASA Near Earth Network (NEN) that are being considered. The potential NEN enhancements include upgrading current NEN Cortex receiver with Forward Error Correction (FEC) Turbo Code, providing X-band uplink capability, and adding ranging options. The benefits of ground station enhancements for CubeSats flown on NASA Exploration Missions (EM) are presented. This paper also describes how the NEN may support lunar and L1/L2 CubeSats without any enhancements. In addition, NEN is studying other initiatives to better support the CubeSat community, including streamlining the compatibility testing, planning and scheduling associated with CubeSat missions.

INTRODUCTION

The Near Earth Network (NEN) has been in discussions with approximately 30 CubeSats planning to launch over the next four to five years, ranging in orbit from low Earth orbit (LEO) to lunar.

For CubeSats, designing the data transmission from Low Earth Orbit (LEO) can be a significant challenge. That challenge is exacerbated for CubeSats that have an operating region in lunar space. One of the largest such challenges is overcoming the free space loss.

For LEO missions, a CubeSat with a 1W X-band transmitter, and a 5 dB gain antenna, could achieve a 130 Mbps data rate with the NASA NEN, subject to National Telecommunications and Information Administration (NTIA) bandwidth restrictions. A CubeSat with a 1W S-band transmitter and a 0dB gain antenna could achieve a 500 kbps data rate with the NASA NEN.

Typical LEO CubeSats have an orbital altitude of 400 km (248 mi), while lunar CubeSats operate 400,000 km (248,000 mi) away from the earth. This means transmitting a signal at the same data rate as LEO requires 1,000,000 times the power, the equivalent of 60 decibels (dB).

There are multiple approaches to solve this problem. See Figure 1. Case 1 represents a standard S-Band CubeSat design in LEO. Cases two through four are at lunar distances. Case 2 represents a CubeSat with an improved spacecraft antenna and a 4 Watt transmitter downlinking to the NASA NEN Wallops Ground Station at 16 kbps at X-Band. Case 3 represents a CubeSat with an improved spacecraft antenna and a 4 Watt transmitter downlinking to Swedish Space Corporation (SSC): Dongara, Australia at 32 kbps at X-Band. Case 4 represents a CubeSat with an improved spacecraft antenna and a 4 Watt transmitter downlinking to the Morehead State University (MSU) Ground Station at 60 kbps at X-Band.

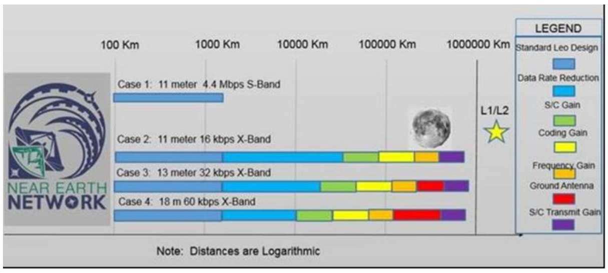


Figure 1: Design Trades to Communicate with Lunar CubeSats

In transitioning from LEO to lunar and L1/L2 distances, reducing the data rate by a factor of 100 is worth 20 dB. Higher performance ground antennas could add another 20 dB. Using directional flight antennas on the CubeSat could add 6 dB. Other enhancements such as more efficient coding techniques could add over 4 dB gain compared to conventional convolutional coding for lunar and L1/L2 distances.

Navigation for LEO CubeSats is relatively easy compared to lunar and L1/L2 CubeSats. LEO CubeSats could use North American Aerospace Defense Command (NORAD) radar tracking for two-line element ephemeris. LEO CubeSats could also use the Global Positioning System (GPS) for navigation. Neither NORAD nor GPS is available for lunar and L1/L2 CubeSats.[1] Large ground aperture antennas and significant CubeSat power are required in order to detect the signal and close the link for tracking. The NEN is investigating the use of Doppler and ranging to support the navigation needs of lunar and L1/L2 CubeSats.

Lunar and L1/L2 CubeSats must also survive in a harsher radiation environment than LEO CubeSats.

There are multiple S-, X-, and Ka-band flight radio and antenna options available to CubeSats for LEO. Some integrated CubeSat bus manufacturers are including options for NEN-compatible flight radios. Additional constraints have resulted in there being less flight hardware options available for lunar and L1/L2 orbits.

The Lunar IceCube mission offers an excellent opportunity to study the challenges and design tradeoffs associated with meeting communication and navigation needs for lunar and L1/L2 CubeSats. There are measures that could be taken with the flight equipment as well as the MSU and NASA NEN ground stations to ease the burden of limited Size, Weight and Power on such CubeSats.

NASA's NEN is evolving to meet the needs of future missions. NEN offers high-gain ground system solutions for Exploration Mission 1 (EM-1) and future exploration CubeSat missions with assets around the globe, including NASA NEN and NEN commercial ground systems. Commercial ground station providers include Kongsberg Satellite Services (KSAT), and Swedish Space Corporation (SSC) and its subsidiaries.[2]. See Figure 2.

Communication services are provided for various low-Earth orbits (LEO), geosynchronous orbits (GEO), highly elliptical orbits (HEO), LaGrange orbits, lunar, L1/L2 and suborbital, and launch trajectories.

The frequency bands supported by NEN are Ka-, X- and S-band. NEN apertures range in size from 4.7-m to 15-m, having an average aperture size of ~11m, with the exception of an 18-m Ka- and S-band antenna at the White Sands Station. NEN is the process of adding additional antennas to meet the needs of future Ka-band missions in orbits ranging from LEO to L1/L2.

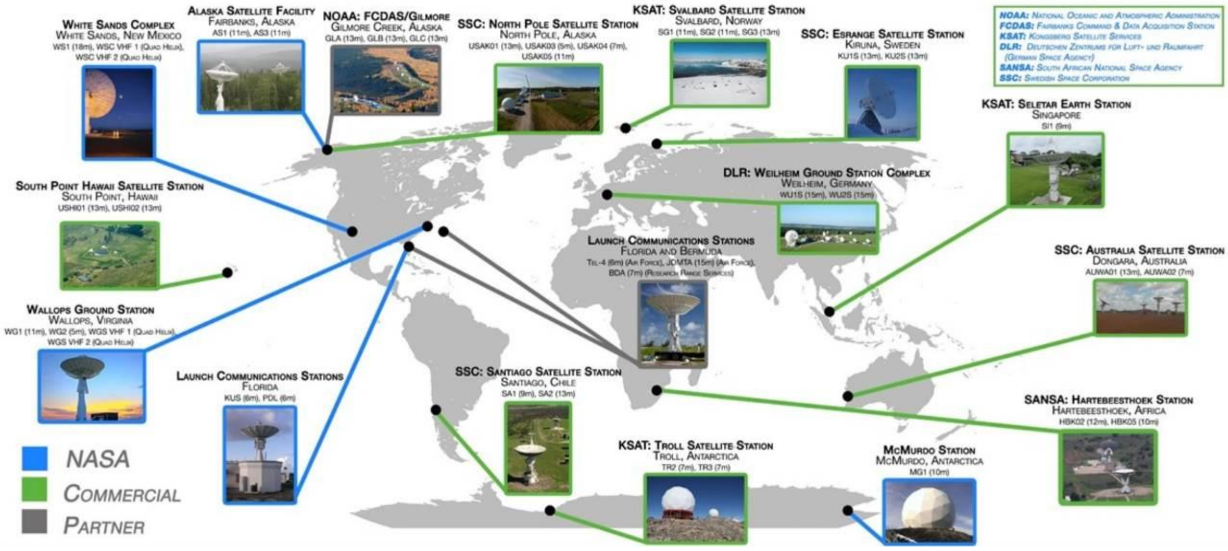


Figure 2: The NEN Supports Orbits in the Near Earth Region from Earth to 2 Million Kilometers

EM-1 CUBESATS & LUNAR ICECUBE MISSION OVERVIEW

A new era of solar system exploration is being ushered in by NASA's EM-1. EM-1 is the designation given to the maiden voyage of NASA's Space Launch System (SLS). SLS will support human exploration beyond LEO and will also serve as a platform to launch small satellites as secondary payloads to Earth escape. NASA has selected 13 secondary payloads to launch on EM-1, all 6U CubeSats will perform science investigations that address NASA Strategic Knowledge Gaps.

CubeSats are "nanosatellite" class research spacecraft that are built in standardized units. The standard unit (U), is 10 cm × 10 cm × 11 cm, and has a mass of 1.33 kilograms per U. A variety of enabling technologies, including electric propulsion, solar sail technologies, miniature science instruments, radiation tolerant processors, precise attitude control systems, compact ranging transponders and high data rate communication systems, will be demonstrated by these missions. Innovative low energy manifold trajectories will be employed to allow the spacecraft to travel to deep space destinations with limited propellant mass and constrained delta-v. The 13 secondary payloads to be deployed on EM-1, including Lunar IceCube, will usher in a new era of solar system exploration with small satellite platforms.

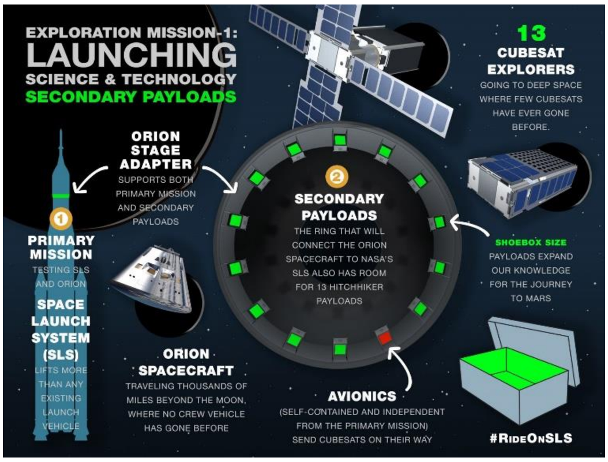


Figure 3: Exploration Mission-1 Secondary Payloads

Lunar IceCube is one of several public-private partnership missions chosen under NASA's NextSTEP (Next Space Technologies for Exploration Partnerships) Broad Agency Announcement for the EM-1 mission. In addition to providing useful scientific data, Lunar IceCube will help inform NASA's strategy for sending humans farther into the solar system.[3] The ability to search for useful assets can potentially enable astronauts to manufacture fuel and other provisions needed to sustain a crew for a journey to Mars, reducing the amount of fuel and weight that NASA would need to transport from Earth.[4]

The scientific goal of the Lunar IceCube is to prospect for water in solid (ice), liquid, and vapor forms and other lunar volatiles from a low altitude (targeting 100 km) lunar orbit. The mission will address NASA Strategic Knowledge Gaps related to lunar volatile distribution by focusing on the abundance, location and transportation physics of water ice on the lunar surface at a variety of latitudes, thus not restricted to permanently shadowed regions (PSRs).

Lunar IceCube extends the findings of previous missions. The Lunar IceCube measurements will completely encompass the broad 3 µm band resulting from absorption by several forms of water instead of cutting off at 3 µm as previous near infrared (NIR) spectrometers have done.[5,6]

The mission is a partnership between lead institution MSU, NASA Goddard Spaceflight Center (GSFC), Jet Propulsion Lab (JPL), the Busek Company, and Vermont Technical College. Lunar IceCube will be deployed during lunar trajectory by the SLS on Bus Stop One and use an innovative RF Ion engine (the BIT-3 developed by Busek) and an innovative low energy manifold trajectory (modeled by GSFC's Flight Dynamics Facility) to achieve lunar capture and the science orbit.

Lunar IceCube and its companion EM-1 CubeSats have the potential to prove the utility of small satellite platforms, particularly the CubeSat standard, for lunar and planetary exploration. The EM-1 CubeSats, while performing informative science missions, will demonstrate several enabling technologies that are required for interplanetary operations, including electric propulsion, miniaturized high-performance science instruments, radiation hardened CubeSat subsystems, innovative thermal management systems, and the implementation of navigation and ranging systems. New processes are required to be developed to send these spacecraft to distant destinations with limited propellant. Low energy manifold trajectories are the key enabling process that makes the use of low thrust systems possible and the use of extensive numerical modeling of these trajectories along the interplanetary superhighway has made the use of these complex trajectories a reality. All of these technologies and processes have matured to the point of enabling interplanetary SmallSat missions. One of the most challenging of these technologies and processes, communications and ranging, particularly during the critical deployment state at Earth escape, is considered herein.

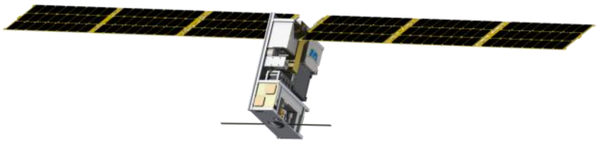


Figure 4: The Lunar IceCube Spacecraft in Development by MSU and its Partners NASA GSFC, JPL, Busek and Vermont Technical College

COMMUNICATION & NAVIGATION NEEDS FOR LUNAR ICECUBE MISSION

Lunar IceCube navigation and communication poses significant challenges, including orbit determination immediately after deployment required to finalize lunar flyby maneuver plans and establishing links to the CubeSat with limited transmitter power while in the transfer trajectory and as it approaches the moon. A distinct advantage of tracking a satellite on a direct transfer to the moon or in a lunar transfer orbit, on the other hand, is the extended "hang time" above the ground station, which increases as it approaches the moon. Figure 5 provides an illustration of the current mission design and a proposed operational timeline that supports BIT-3 (Busek Ion Thrusters) low-thrust maneuver planning, telemetry and commanding, and science data return. In addition, all communication and tracking is provided by the Iris-V2 transponder connected to a "medium gain antenna".

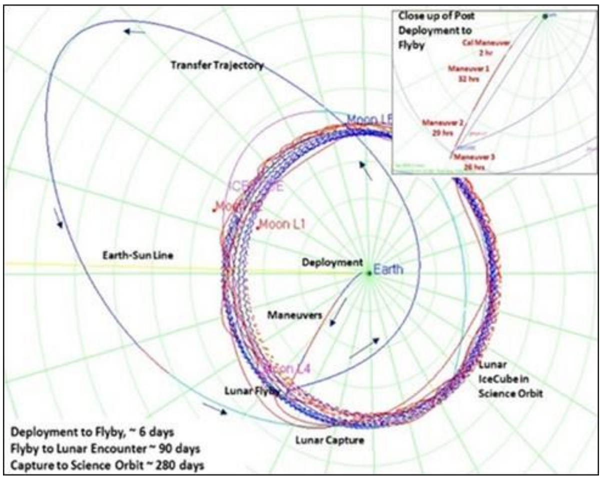


Figure 5: Lunar IceCube Mission Design

To meet these challenges, a large aperture is required on the ground. NASA's Deep Space Network (DSN) is oversubscribed to guarantee critical communications, especially post deployment (1-2 days) and support of lunar capture (2-3 months). Ground operations (tracking and telemetry) from launch to early operations and through primary mission operations and termination procedures will be managed by MSU. MSU operates a 21-m Ground Station that will serve as a dedicated

Earth station for the mission and will provide significant gain and link margin to acquire telemetry daily and have frequent opportunity for commanding the satellite systems during the operational phase of the mission. As a significant addition to the MSU facility, the NEN can provide comprehensive tracking and telemetry services from facilities around the globe. An agreement and coordination with NEN was initiated to acquire the desired additional facilities for post deployment events, telemetry, and additional routine and critical event (lunar insertion) navigation support.

Lunar IceCube's sophisticated manifold transfer trajectories require a robust Guidance Navigation and Control (GNC) approach, which will utilize components of the attitude control system, communication system, and propulsion system (thrusters).[7,8,9,10] The navigation effort is performed by GSFC flight dynamics using the secured Flight Dynamics Facility (FDF), which routinely receives tracking data from NEN. GSFC will provide for both navigation and maneuver planning to ensure the trajectory design is successful. FDF provides for the planning, ephemeris generation, tracking evaluation, and operational support products, as well as data archiving. Routine FDF tracking and data product interfaces via secured services will be provided. Required tracking data and related accuracies vary over the transfer trajectory. During the period from deployment to lunar gravity assist, tracking is necessary between low thrust maneuvers over a ~6-day duration. Post lunar flyby, tracking can be reduced to several 3-hour passes per week with increased tracking around specific critical event periods, e.g. correction and momentum unload maneuvers. After Lunar IceCube is captured into a three-body orbit about the moon, tracking is interspersed with long maneuvers until a stable transition orbit (two-body) is achieved, about 4 weeks. Once in this transition orbit, tracking durations of several hours per week will be satisfactory to plan remaining maneuvers. Once in the science orbit, tracking is required every 2-3 days. Navigation accuracies of <100 m in position and <0.1 cm/s in velocity are required for the entire design. To enable these orbit determination accuracies, tracking measurement data should meet or exceed current NEN support for the Deep Space Climate Observatory (DSCOVR) mission. To complete the transfer and insertion into the science orbit, a total of 1300 m/s over 219 days of thruster is required. Unfortunately, due to onboard power availability on Lunar IceCube, tracking is only permitted during non-maneuver arcs, e.g. post deployment, between outbound maneuvers, post flyby and into the transfer and at certain intervals during the long term low thrust maneuvers to attain the science orbit.

POTENTIAL CUBESAT RADIOS AND ANTENNAS FOR LUNAR AND L1/L2 MISSION

CubeSat radios and antennas are important components of CubeSats considering power, pointing and real estate (mass) limitations of CubeSat missions. CubeSat radios and antennas mainly operate at UHF, S- and X-bands and some missions are considering Ka-band and laser communication in the future. Table 1 presents select CubeSat radios and

Table 2 presents select CubeSat antenna types at different operating frequencies. All of these selected communication systems should be compatible with NASA Communication infrastructure. Some vendors claimed compatibility with NASA networks. However, communication systems without flight heritage must successfully complete a compatibility test with GSFC Compatibility Test Laboratory (CTL) in order to be considered as truly NASA NEN and Space Network (SN) compatible.

Most of the EM1 CubeSat missions proposed to use X-band Iris Radio and 4 patch antennas with 7 dBi maximum gain. Since Iris transponder does not have a diplexer, two of these patches will be used for transmit and other two will be used for receive. Each pair of antenna will provide omni (spherical) coverage around the cube satellite.

Lunar IceCube Mission Communication System

Lunar IceCube communication system consists of 4 X-band patch antennas and an Iris transponder without a diplexer.

Lunar IceCube X-band Patch Antenna

Lunar IceCube will use 4 custom design X-band patch antennas. Below are some of the specs for the patch antennas.

Patch Antenna Performance Characteristics:
– Receive Band: 7.145-7.190 GHz
– Transmit Band: 8.400-.8.450 GHZ
– Return Loss >18dB
– TX/RX Isolation >35dB
– Mass: 40 gr each
– Gain: 7 (6) dBi

Table 1: Lunar and L1/L2 CubeSat Radios

Freq.	Vendor / Name	Size (cm)	Mass (g)	Flight Heritage	Max Data Rate	Modulation; FEC	NASA Network Compatibility
S-Band	Innoflight / SCR-100	8.2x8.2x3.2	300	Sense NanoSat	4.5 Mbps Tx	BPSK, QPSK, OQPSK GMSK, FM/PCM; Conv. and R/S	NEN, SN, DSN
	Tethers Unlimited / SWIFT-SLX	10x10x3.5	380	None	15 Mbps Tx	Rx/Tx: BPSK/QPSK Tx:8PSK/16APSK/32APSK OQPSK, GMSK PM, CPM SGLS-Ternary, Spread-spectrum; Reed-Solomon w/ interleaving Convolutional w/ puncturing Soft-Viterbi BCH, CRC, Turbo/LDPC	NEN, SN, DSN
	Clyde Space / S-Band TX (STX)	9.6x9.0x1.6	< 80	UKube-1	2 Mbps Tx	QPSK	Partially NEN
	Microhard / MHX-2420	8.9x5.3x1.8	75	RAX	230 kbps Tx 115 kbps Rx	FSK	Partially NEN
	Quasonix / nano TX	3.3x3.3x3.3	<200	CPOD	46 Mbps Tx	PCM/FM, SOQPSK-TG, Multi-h CPM, BPSK	NEN
X-Band	LASP & GSFC / X-band Radio	9.8x9x2	500	None	12.5 Mbps Tx 50 kbps Rx	BPSK, OQPSK; R/S and Conv.	NEN
	Syrlinks / X-band Transmitter	9x9.6x2.4	225	None	5 Mbps Tx	BPSK, OQPSK; R/S and Conv.	NEN
	Marshall / X-band Tx	10.8x10.8x7.6	<1000	FASTSat2	150 Mbps Tx 50 kbps Rx	BPSK, OQPSK; LDPC 7/8	NEN
	Tethers Unlimited / SWIFT-XTS	8.6x4.5 (0.375U)	500	None	300 Mbps Tx	Rx/Tx: BPSK/QPSK Tx:8PSK/16APSK/32APSK OQPSK, GMSK PM, CPM SGLS-Ternary, Spread-spectrum; Reed-Solomon w/ interleaving Convolutional w/ puncturing Soft-Viterbi BCH, CRC, Turbo/LDPC	NEN, SN, DSN
	JPL / Iris Transponder	0.4U	400	INSPIRE	62.5 Kbps Tx 1 kbps Rx	BPSK bit sync, CCSDS frame size	DSN, Partially NEN
Ka-Band	Canopus Systems / Ames Ka-band Tx	18x10x8.5	820	None	125 Mbps Tx	{Q,8,16A,32A}PSK, DVB-S2, CSSDS, LDPC Concatenated with BCH	NEN, SN, DSN
	Tethers Unlimited / SWIFT-KTX	8.6x4.5 (0.375U)	500	None	300 Mbps Tx	{Q,8,16A,32A}PSK, DVB-S2, CSSDS	NEN, SN, DSN

Table 2: Lunar and L1/L2 CubeSat Antennas

Antenna Vendor	Antenna Type	Band	Antenna Gain	Dimensions	Mass (g)
Antenna Development Corporation	Low-Gain Patch Antenna (LGA)	S	2	4x4x0.25"	115
Haigh Farr	Patch	S	2	9.4x7.6x4cm	62
University of Southern California’s Information Sciences Institute Space Engineering Research Center (SERC)	Deployable High Gain Antenna	S and X	>24	50 cm deployed diameter	760
BDS Phantom Works	Deployable High Gain Antenna	S	18	50 cm deployed diameter	1000
Antenna Development Corporation	Patch Array	X	9	1.85x1.85x0.55"	300
BDS Phantom Works	Deployable High Gain Antenna	X	25	50 cm deployed diameter	1000
Canopus Systems	Horn	Ka	25	18 cm deployed diameter	820

Iris Transponder

The Iris transponder was designed by JPL to answer the need for a Software Defined, radiation tolerant radio, to fit the volume and space constraints of small CubeSats. Iris v2.1 was chosen by Lunar IceCube as their communications device.

Iris Layout and Design

One of the main advantages of the Iris design is its modularity. The user is able to select the layers necessary for the particular mission, be it S-band, X-band, Tx or Rx. A typical configuration takes up 0.5U and weighs about 1.2 kg. The Low Noise Amplifier (LNA) and Solid State Power Amplifier (SSPA) necessary to complete the design are housed in their respective shells. As shown in Figure 6, the SSPA has RF paths for 3 antennas, while the LNA is capable of connecting to up to 2 antennas, allowing for redundancy, increased coverage and flexibility for the mission. The power consumption is selectable according to the phase of operations, ranging from 12.6W DC in receive only mode (X-band), and 35W input in full transponder mode, generating 3.8W output.

Iris Data Rates Supported

Iris supports in-flight switchable discrete data rates. The Lunar IceCube CubeSat, for example, may be tracked by several different ground stations belonging to the DSN, the NEN, and the ground station at MSU, each having different antenna sizes and gain to noise temperature (G/T) characteristics. For this reason, and accounting for orbit/range variations, the Lunar IceCube mission is exploring implementation of download data rates of 16, 32, 64, 128 kbps. Upload/command data rates are similarly selectable from a high of 8 kbps, down to 62.5 bps, decreasing in steps of powers of two.

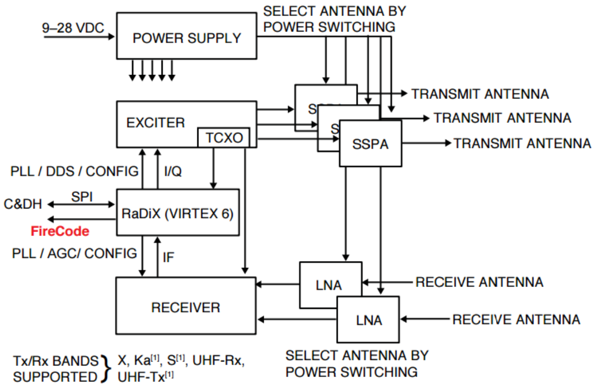


Figure 6: Iris v2.1 Block Diagram

Iris Radiation Tolerance

One feature that sets the Iris apart from other Commercial Off-the-Shelf (COTS) radios is the fact that it is rated up to 15 krad Total Ionizing Dose (TID). Its memory modules (32 Mbit non-volatile NOR-Flash, 16Mbit volatile SRAM and 4Mbit EDAC SRAM) are all radiation tolerant.

Iris Telemetry Encoding

Besides the widely used Convolutional and Reed Solomon encoding, the Iris is also capable of using Turbo Convolution Codes, "whose performance in terms of Bit Error Rate (BER) are close to the Shannon limit"[11], see Figure 7.

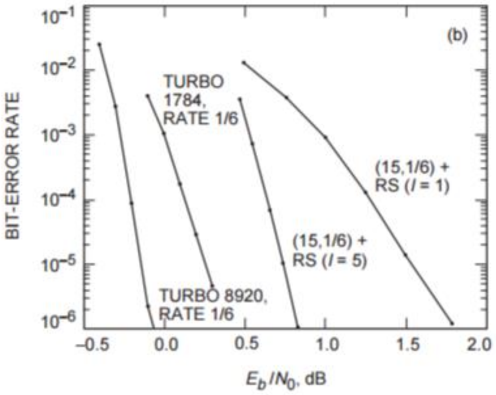


Figure 7: Bit Error Rate Comparison

Lunar IceCube Mission Radiation Requirement

GSFC radiation branch performed an analysis for Lunar IceCube. The radiation environment during Lunar IceCube trip to the moon, and while it is orbiting the moon, is harsh from a Galactic (Heavy Ion) Radiation perspective, because it is outside the protective magnetic field of the earth. Non RAD hard electronics will likely suffer Single Event Effects (SEEs) and more importantly, Single Event Latch ups (SELs) may result in mission ending failures. Also, the trips through the Van Allen belts early in the mission will expose the mission mostly to Total Ionizing Dose (TID) Radiation and not very much Heavy Ion, thanks to Earth's magnetic field.

Below are Radiation Requirements for Lunar IceCube.

The Direct Radiative Effect (DRE) Electrical, Electronic, and Electromechanical (EEE) Parts shall meet Linear Energy Transfer Threshold (LETth) of > 37 MeV-cm2/mg for soft errors from single events (SEU, Single Event Transients, etc.).

The DRE EEE Parts shall meet LETth of > 75 MeV-cm2/mg for potential destructive events (SEL, SEB, SEGR, etc.). The DRE EEE Parts shall meet 5 krads (Si) Total Ionizing Dose (TID) assuming 50 mil Al shielding.

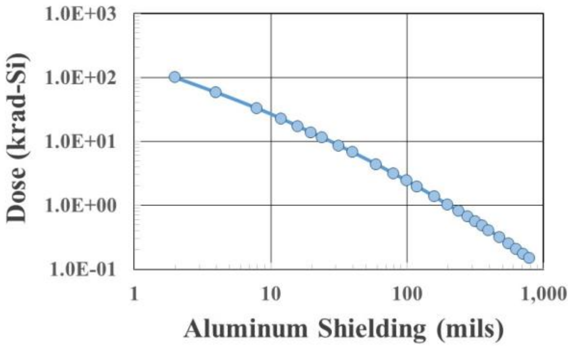


Figure 8: Lunar IceCubeDose - Depth at 95% Confidence

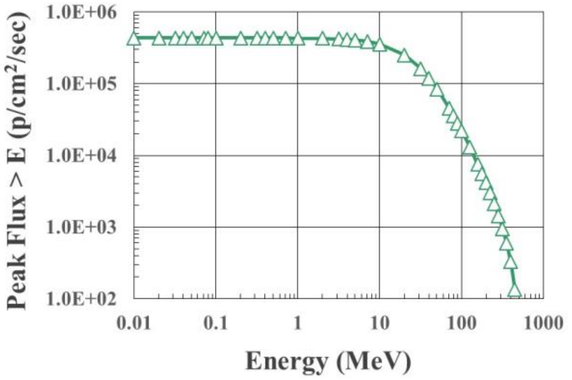


Figure 9: Lunar IceCube Worst Case Proton Fluxes - 100 mils Al

LUNAR ICECUBE NASA NEN GROUND STATION COVERAGE AND LINK ANALYSIS

Approximately 3.5 hours after launch, Lunar IceCube will be deployed with five EM-1 CubeSats at Bus Stop #1 at a distance of approximately 25,000km.[12] A preliminary model of the trajectory, as of the writing of this paper, was developed and used to simulate ground station coverage times. The Lunar IceCube trajectory consists of a series of maneuvers and cruise periods, starting with deployment and continuing through the science phase in lunar orbit. The significance of the maneuver times is that Lunar IceCube will be unable to communicate during maneuvers due to power limitations. Therefore, the coverage analysis focuses on the cruise periods, when communication will be possible. For the purposes of the coverage analysis[13], the Lunar IceCube trajectory has been broken up into three phases, presented in Table 3 and depicted in Figure 10.

Table 3: Lunar IceCube Trajectory Phases

Phase #	Phase Name	Duration	Description
1	Deployment	~4 days	Begins with an 8-hour cruise event followed a series of three maneuver and cruise events
2	Trans-lunar Injection	~272 days	A series of four long duration maneuver and cruise events leading to lunar orbit
3	Science Orbit	~100 days	An iterative series of 2 hour maneuvers followed by a single 3 - 5-hour cruise event

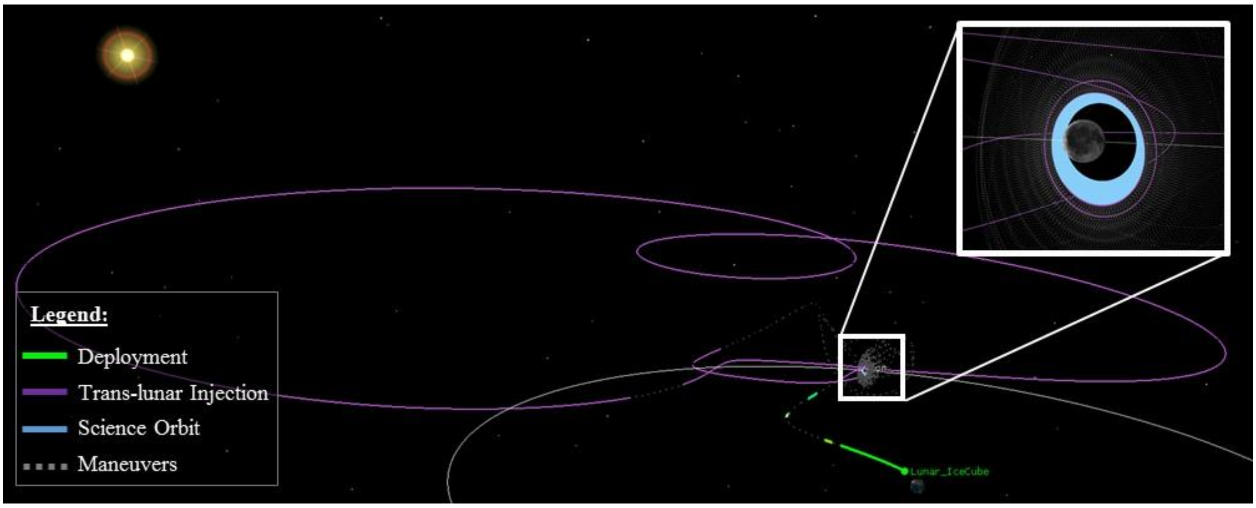


Figure 10: Graphic of Lunar IceCube Trajectory by Phase

Lunar IceCube DSN/MSU Support Coverage

The DSN in conjunction with MSU will provide prime support to Lunar IceCube during all three phases of the mission. The Deployment phase has been deemed critical, specifically the initial 8-hour cruise event, as the Lunar IceCube project will desire as much tracking data as possible to ensure a series of successful burns. While the DSN and MSU are prime, the NEN would be in a position to provide additional, significant comprehensive tracking and telemetry. Although MSU will have visibility of the critical 8-hour cruise event during the Deployment phase, it will not have visibility for the entirety of the remaining three cruise events during the Deployment phase. While the DSN is expected to have complete coverage of the entire Lunar IceCube trajectory (dependent on minimum elevation angle), there will be multiple CubeSats deployed at Bus Stop #1, which could lead to scheduling and resource constraints that prevent Lunar IceCube from getting the desired contacts. Additionally, the DSN with MSU will have lengthy periods, in all three phases, when only one site will have coverage. Figure 11 shows the total number of DSN sites, including MSU, that have coverage of Lunar IceCube over the entire trajectory file. The coverage times assume a minimum elevation angle of 6 degrees (Note: For planning purposes DSN assumes 6 degrees for downlink and 10 degrees for uplink). The percent of time associated with zero site coverage is due to lunar occultations and not a gap in DSN/MSU coverage.

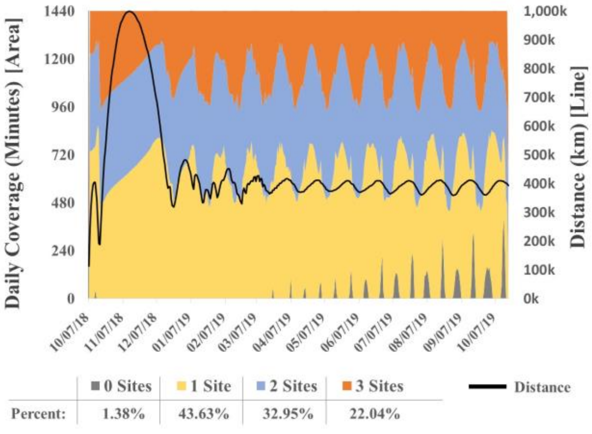


Figure 11: DSN/MSU Coverage to Lunar IceCube

Supplemental NEN support could ensure there is a minimum of two sites in view of Lunar IceCube at all times, except for lunar occultations. Therefore, it would be advantageous if the NEN had assets that could provide the complementary coverage and be available for supplemental and backup support to Lunar IceCube.

Potential Additional NEN Support and Site Selection

The location of NEN sites was presented in Figure 2. Due to the trajectory of Lunar IceCube and the use of the Iris radio for X-band downlink and uplink, equatorial NEN sites offering X-band service would be most desirable. The number of NEN sites considered for support would depend on the desired amount of coverage.

The NEN currently utilizes two equatorial commercial sites, SSC Hawaii and SSC Australia, that have 13m antennas capable of supporting X-band uplink and downlink, making them ideal for Lunar IceCube support. Currently these are the only two NEN sites capable of supporting X-band uplink. While the sites support X-band uplink, modifications would be required for compatibility with Lunar IceCube.

One or two additional NEN sites could be selected to provide near-full or full coverage, respectively. The NEN Wallops site has an 11-m system capable of supporting X-band downlink. The NEN Wallops site, in conjunction with SSC Hawaii and SSC Australia, would provide near-full coverage to Lunar IceCube, except for a gap over the Indian Ocean. Of the remaining NEN sites, the commercial South African National Space Agency (SANSA) site in Hartebeesthoek would be ideal to close the gap and allow the NEN to provide full global coverage. The SANSA Hartebeesthoek site currently houses a 10m antenna capable of supporting X-band downlink.

Link Analysis

A NEN support link analysis was performed to evaluate the feasibility of X-band communication support for Lunar IceCube science data downlink.[14] The analysis determined the achievable data rates from four NEN ground stations with the link parameters defined in Table 4.

Table 4: IRIS X-band Downlink Parameters

Parameter	Value
S/C Altitude	400,000 km
Rain Availability	99%
Frequency	8475 MHz
Transmit Power	4 Watts
Passive Loss	1 dB
Antenna Gain	6 dBi
Polarization	RHCP
Polarization Loss	0.5 dB
Modulation	BPSK
Data Format	NRZ-L
Telemetry Coding	Turbo (8920, 1/6)
Required Eb/No	-0.14 dB (BER=10^{-5}@ Rate 1/6 Turbo Decoder)

The Iris transponder does not support a continuous range of data rates, but rather discrete rates (1, 8, 16, 32, 64, 128, 256 kbps). Based on the link analysis, a summary of the achievable data rates for the spacecraft using the Iris transponder at a range of 400,000 km is given in Table 5.

Table 5: Achievable Data Rates at a Range of 400,000 km

Station	X-band G/T (dB/K) *	Achievable Rate
Wallops	35.4	16 kbps
Australia	37.7	32 kbps
Hawaii	37.7	32 kbps
Hartebeesthoek	30.5	8 kbps

* Clear sky and 10° elevation angle

The achievable data rate is 64 kbps at a 400,000 km range for the MSU 21-m antenna system.

Additional achievable data rates analyses were performed for Lunar IceCube during various events, including deployment, pre-bound lunar flyby, outbound lunar flyby, Earth perigee, and outbound crossing of lunar orbit. Achievable data rates will vary depending on the distances to the Earth during these events.

Ranging

Ranging will be used when needed for orbit determination. As of the writing of this paper, Lunar IceCube has not decided whether sequential tone ranging or Pseudo-Noise (PN) ranging will be used for the spacecraft ranging.

If sequential tone ranging is used, there will be two modes for uplinks and one mode for downlink.

1. Ranging data channel having a major tone for uplink.

2. Command data channel modulating a subcarrier with a ranging data channel having a major tone for uplink.

3. A single tone ranging channel directly phase modulating the RF carrier for downlink

Ranging tones are transmitted from the ground station to Lunar IceCube via X-Band uplink. Frequency tones are phased modulated on the uplink carrier via X-Band. The spacecraft (S/C) Iris transponder returns these tones on the X-Band downlink to the station. The station ranging system determines the distance of the S/C by measuring the time delay between the transmitted and received tones. High frequency tones provide system accuracy and low frequency tones provide distance ambiguity resolution.

Ranging can be performed simultaneously with commanding or alone. It will be employed when there is no telemetry data on the downlink.

JPL is testing the Iris transponder PN ranging during the summer of 2017.

The ranging parameters, such as tone frequencies and modulation indexes, have not been finalized yet.

NEN Coverage: Deployment Phase

The critical Deployment phase, as defined in Table 3, begins with an 8-hour cruise event. The initial cruise event is followed by a series of maneuvers and additional cruise events as shown in Figure 12.

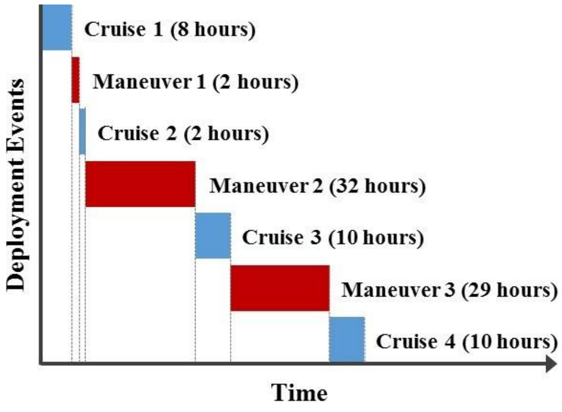
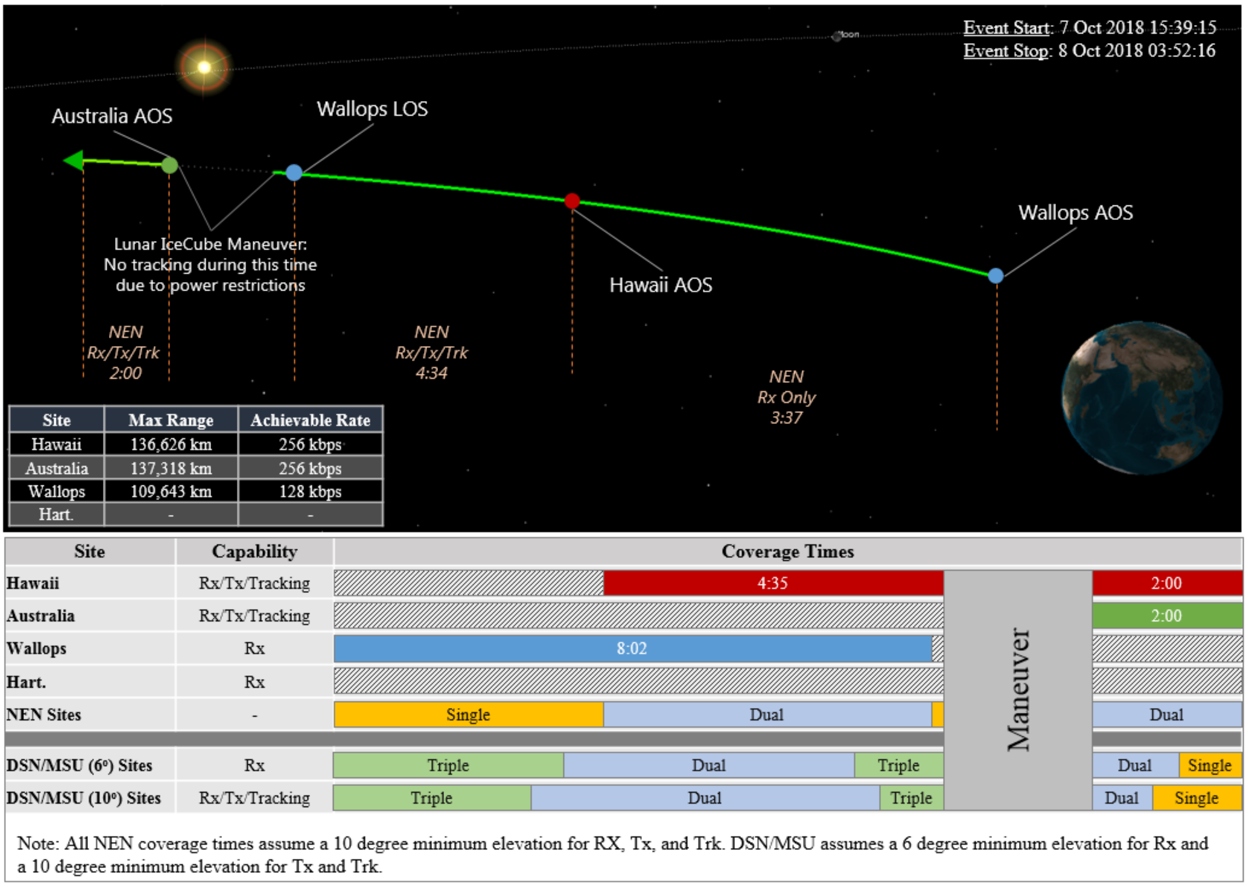


Figure 12: Deployment Phase Events

The NEN would be able to provide complete, single or dual, coverage during the critical Cruise #1 (8 hour) and Cruise #2 (2 hour) events. At initial deployment, only the NEN Wallops station would be in view, which would only be capable of supporting X-band downlink. The NEN SSC Hawaii site would come into view approximately 3 hours and 30 minutes after initial deployment, at which time the NEN would be able to provide downlink, uplink, and tracking (e.g., Doppler or ranging). Following the 2-hour Maneuver #1, both NEN SSC Hawaii and SSC Australia would be in view, allowing for continued downlink, uplink, and tracking support. At this close proximity, the NEN stations would be able to support 256 kbps from the 13m SSC Hawaii and SSC Australia stations, and 128 kbps from the 11-m antenna at Wallops. From Cruise #1 through Cruise #2, the DSN/MSU would have either dual or triple station coverage, except for approximately 1 hour at the end of Cruise #2. The first 2 cruise events are depicted in Figure 13.



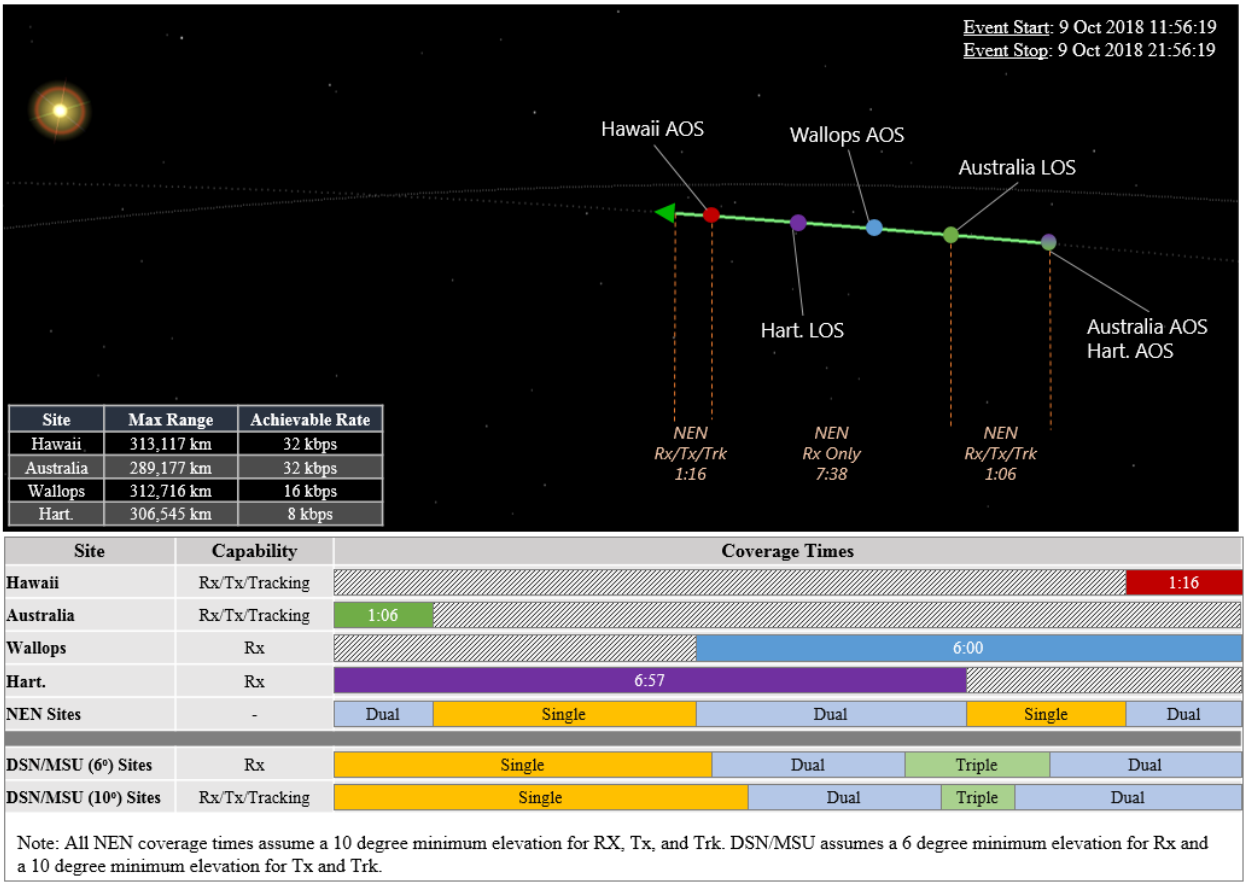
Site	Max Range	Achievable Rate
Hawaii	136,626 km	256 kbps
Australia	137,318 km	256 kbps
Wallops	109,643 km	128 kbps
Hart.	-	-

Site	Capability	Coverage Times		
Hawaii	Rx/Tx/Tracking	▨ 4:35	Maneuver	2:00
Australia	Rx/Tx/Tracking	▨		2:00
Wallops	Rx	8:02		▨
Hart.	Rx	▨		▨
NEN Sites	-	Single Dual		Dual
DSN/MSU (6°) Sites	Rx	Triple Dual Triple		Dual Single
DSN/MSU (10°) Sites	Rx/Tx/Tracking	Triple Dual Triple		Dual Single

Note: All NEN coverage times assume a 10 degree minimum elevation for RX, Tx, and Trk. DSN/MSU assumes a 6 degree minimum elevation for Rx and a 10 degree minimum elevation for Tx and Trk.

Figure 13: Coverage Summary of the Deployment Phase Events Cruise #1 and #2

Following the 32-hour Maneuver #2, Lunar IceCube will move into a 10-hour cruise event, Cruise #3. During this cruise event the NEN would alternate between having single and dual coverage. A majority of this event would only be covered by the two NEN sites that support downlink only (i.e., Wallops and Hartebeesthoek). The two other two NEN sites, supporting downlink, uplink, and tracking, would have coverage during approximately the first and last hour of the event. NEN data rates during this cruise event are reduced compared to the preceding cruise events, with possible rates ranging between 8 and 32 kbps. The DSN/MSU again have complete coverage during this entire event; however, their coverage starts with single station coverage for the first 4 hours of the event. The third cruise event is depicted in Figure 14.



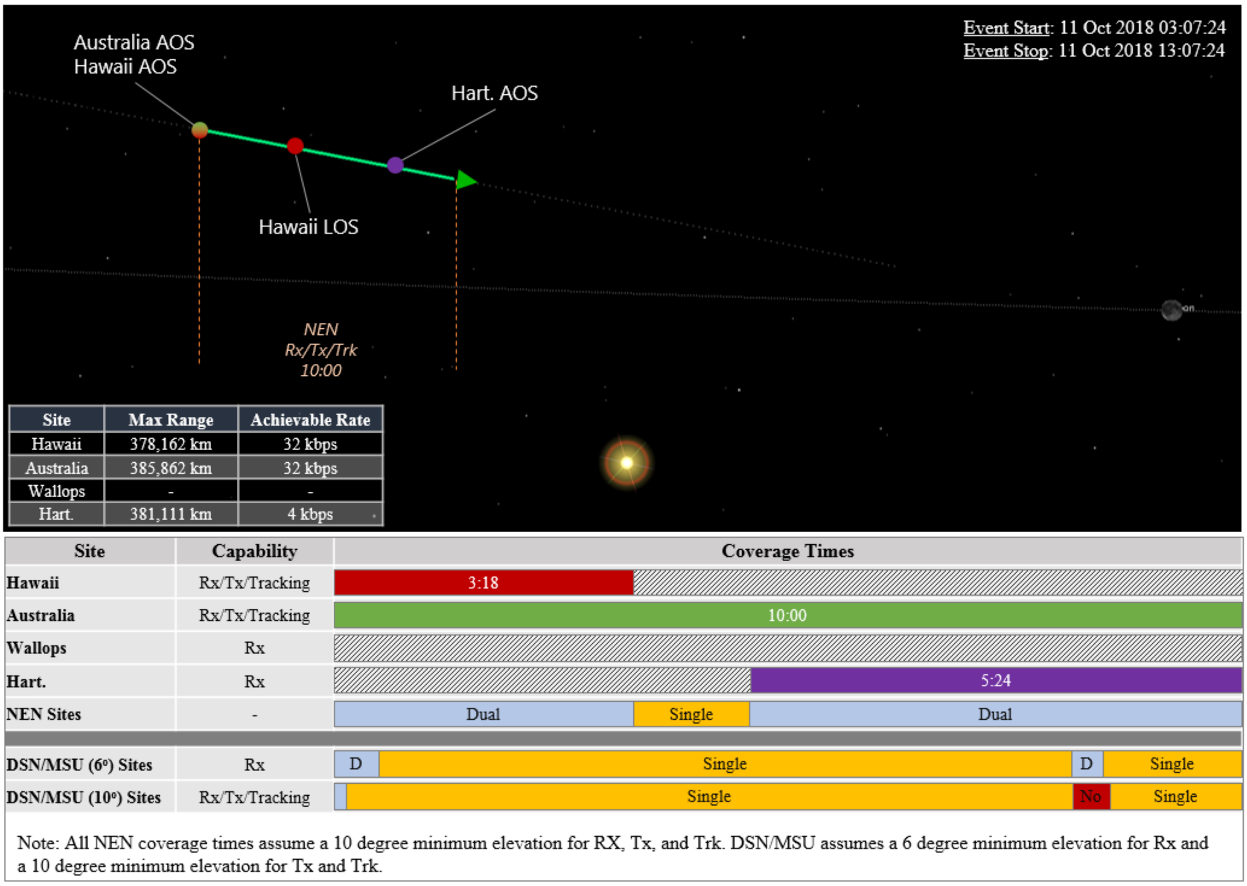
Site	Max Range	Achievable Rate
Hawaii	313,117 km	32 kbps
Australia	289,177 km	32 kbps
Wallops	312,716 km	16 kbps
Hart.	306,545 km	8 kbps

Site	Capability	Coverage Times
Hawaii	Rx/Tx/Tracking	1:16
Australia	Rx/Tx/Tracking	1:06
Wallops	Rx	6:00
Hart.	Rx	6:57
NEN Sites	-	Dual Single Dual Single Dual
DSN/MSU (6°) Sites	Rx	Single Dual Triple Dual
DSN/MSU (10°) Sites	Rx/Tx/Tracking	Single Dual Triple Dual

Note: All NEN coverage times assume a 10 degree minimum elevation for RX, Tx, and Trk. DSN/MSU assumes a 6 degree minimum elevation for Rx and a 10 degree minimum elevation for Tx and Trk.

Figure 14: Coverage Summary of the Deployment Phase Event Cruise #3

The final cruise event in the Deployment phase, Cruise #4, is another 10-hour cruise event following a 29-hour maneuver. A majority of this cruise event is covered by two NEN stations, except for a 1 hour 15-minute period in the middle of the cruise, which is only covered by a single NEN station. The entire cruise event is covered by NEN stations capable of downlink, uplink, and tracking. The achievable NEN data rates for this event are similar to the previous cruise event, ranging from 4 kbps to 32 kbps. The DSN/MSU coverage for this event is mostly single coverage. Towards the end of the event, there is a small, ~30-minute, gap in DSN/MSU coverage, between the DSN Canberra and Madrid sites, if a 10 degree minimum elevation is used. However, that gap would be covered by dual DSN/MSU stations if a 6 degree minimum elevation were used instead. The final cruise event in the Deployment phase is depicted in Figure 15.



Site	Max Range	Achievable Rate
Hawaii	378,162 km	32 kbps
Australia	385,862 km	32 kbps
Wallops	-	-
Hart.	381,111 km	4 kbps

Site	Capability	Coverage Times
Hawaii	Rx/Tx/Tracking	3:18 ▨
Australia	Rx/Tx/Tracking	10:00
Wallops	Rx	▨
Hart.	Rx	▨ 5:24
NEN Sites	-	Dual Single Dual
DSN/MSU (6°) Sites	Rx	D Single D Single
DSN/MSU (10°) Sites	Rx/Tx/Tracking	Single No Single

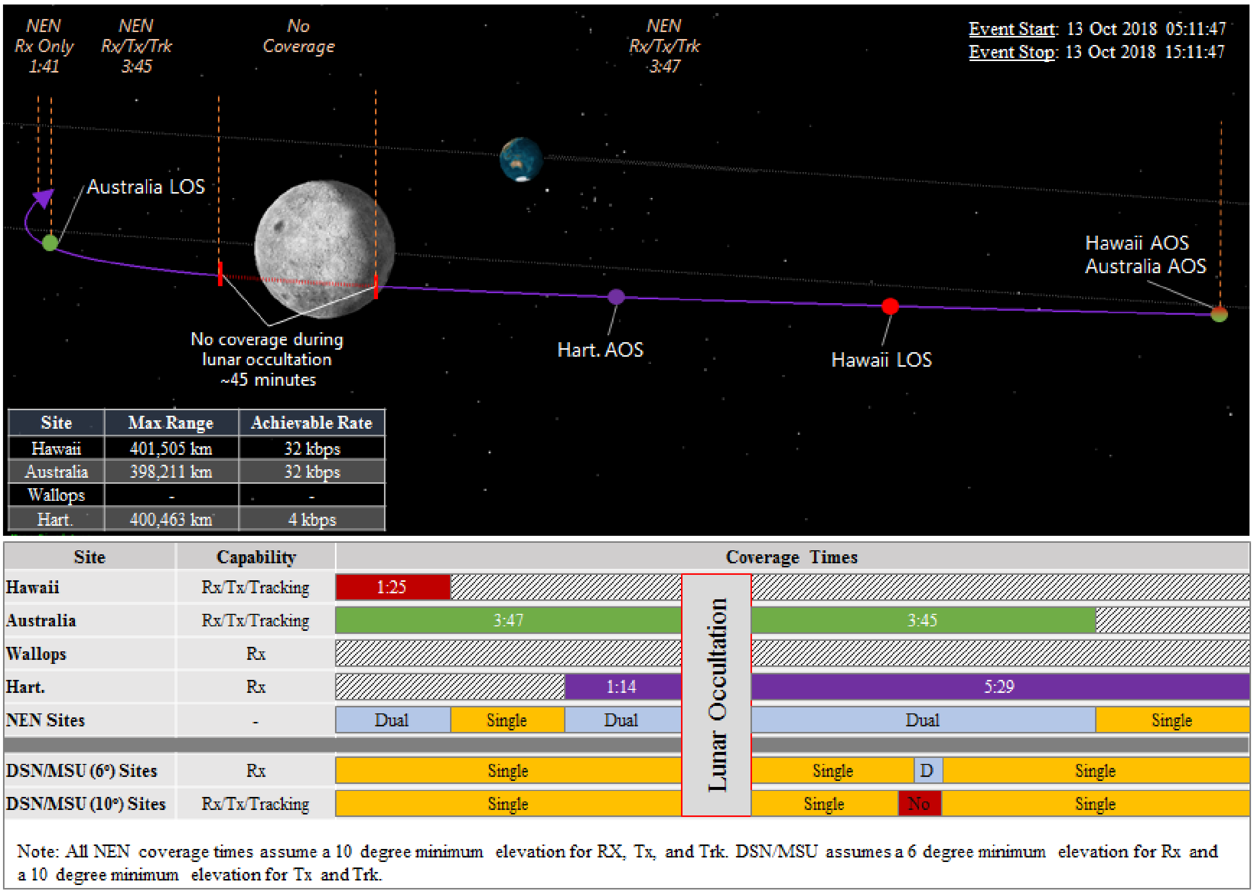
Note: All NEN coverage times assume a 10 degree minimum elevation for RX, Tx, and Trk. DSN/MSU assumes a 6 degree minimum elevation for Rx and a 10 degree minimum elevation for Tx and Trk.

Figure 15: Coverage Summary of the Deployment Phase Event Cruise #4

NEN Coverage: Trans-lunar Injection

The Trans-lunar Injection phase consists of four alternating maneuver and cruise events. Unlike the relatively short maneuver and cruise events during the Deployment phase, the maneuver and cruise events in the Trans-lunar Injection phase are much longer. The cruise events range between 98 hours and 1,352 hours (i.e., 56 days), while the maneuvers range between 26 hours and 4,008 hours (i.e., 167 days). The first cruise event in the Trans-lunar Injection phase contains a number of events of interest, including a Pre-Outbound Lunar Flyby event, an Outbound Lunar Flyby event, an Earth Perigee event, and Outbound Crossing of the Lunar Orbit event. The following three maneuver and cruise events can be described as the lunar capture leading into the Science Orbit phase. For the purposes of this paper, only the Outbound Lunar Flyby event will be presented in detail. The possible coverage during the remaining cruise events will be summarized.

The Outbound Lunar Flyby event occurs towards the beginning of the of the first cruise event, in the Trans-lunar Injection phase, which overall lasts 1,352 hours. Except for the lunar occultation, the NEN would have coverage of Lunar IceCube for the entirety of the event, alternating between single and dual coverage. The NEN would have coverage from SSC Hawaii and or Australia for the entire period prior to the lunar occultation, supporting downlink, uplink, and tracking. Following the lunar occultation, the SSC Australia site would continue to have coverage for another 3 hours and 45 minutes prior to dropping out, leaving only the Hartebeesthoek site able to provide coverage. Achievable data rates would again range between 4 kbps and 32 kbps, with the higher rates associated with the 13m antennas. During this event, the DSN/MSU would primarily have single coverage. There would be a small segment of dual coverage assuming a 6-degree minimum elevation angle. However, if a 10-degree minimum elevation angle was used, there would instead be a small 30 minute gap between Canberra and Madrid coverage. The Outbound Lunar Flyby event is shown in Figure 16.



Site	Max Range	Achievable Rate
Hawaii	401,505 km	32 kbps
Australia	398,211 km	32 kbps
Wallops	-	-
Hart.	400,463 km	4 kbps

Site	Capability	Coverage Times		
Hawaii	Rx/Tx/Tracking	1:25	Lunar Occultation	
Australia	Rx/Tx/Tracking	3:47		3:45
Wallops	Rx			
Hart.	Rx	1:14		5:29
NEN Sites	-	Dual Single Dual		Dual Single
DSN/MSU (6°) Sites	Rx	Single		Single D Single
DSN/MSU (10°) Sites	Rx/Tx/Tracking	Single		Single No Single

Note: All NEN coverage times assume a 10 degree minimum elevation for RX, Tx, and Trk. DSN/MSU assumes a 6 degree minimum elevation for Rx and a 10 degree minimum elevation for Tx and Trk.

Figure 16: Coverage Summary of the Outbound Lunar Flyby

Figure 17 summarizes the NEN coverage during the Trans-lunar Injection phase. The four station NEN architecture would be able to provide dual coverage at any given time for ~71% of the phase, with single coverage available ~29% of the time. The two instances where the graph shows zero NEN site coverage (beginning during lunar flyby and ending during lunar orbit) is due to lunar occultations rather than a gap in NEN coverage. The range during this phase would be between 188k km to 988k km, allowing for NEN data rates between 128 kbps at the nearest distance, assuming a 13m antenna, and 1 kbps at the farthest distance, regardless of antenna size.

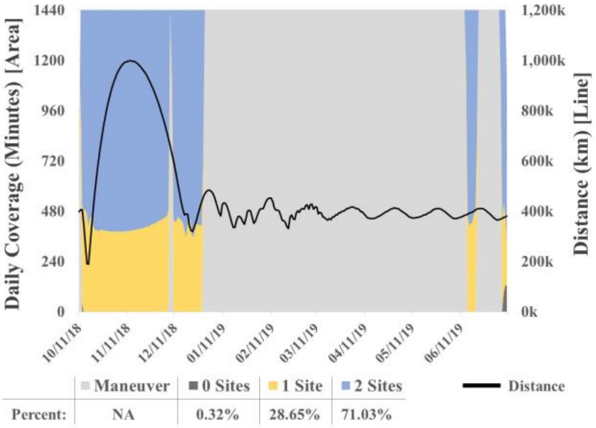


Figure 17: NEN Coverage to Lunar IceCube during TLI Phase

NEN Coverage: Science Orbit

The Science Orbit phase consists of a near steady-state series of maneuvers and cruise events. The analyzed trajectory file has 2-hour maneuvers followed by cruise events that start around 5 hours in duration, but are reduced to roughly 3 hours towards the end of the trajectory data. Since this phase has Lunar IceCube in lunar orbit, there will be a series of lunar occultations where coverage will be dropped due to loss of line of sight. This, in combination with the orientation of the Earth during cruise events, will result in ground station coverage varying over the 100 days of trajectory analyzed, see Figure 18 for an example of Lunar IceCube in lunar orbit.

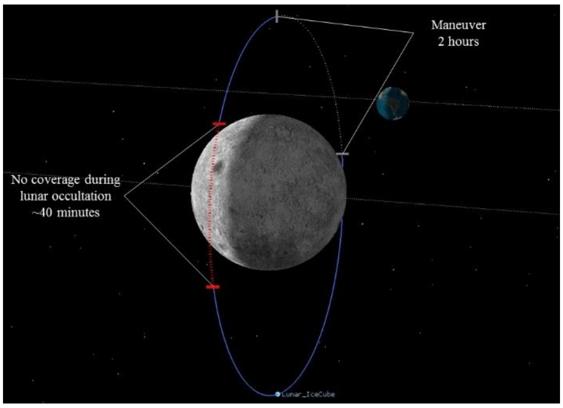


Figure 18: Lunar IceCube Science Orbit Example

Figure 19 summarizes the NEN coverage during the Science Orbit phase. The four station NEN architecture would again be able to provide dual coverage during 68% of the phase, with single coverage available 28% of the time. While Lunar IceCube is in lunar orbit, the frequency of the lunar occultations increase, resulting in no NEN coverage for 4% of the time. Note, the figure below does not account for the 2-hour maneuvers conducted each orbit when communication will not be possible. The range during this phase would be between 359k km to 410k km, allowing for achievable data rates between 4 and 32 kbps, depending on the station.

Figure 19: NEN Coverage to Lunar IceCube during Science Orbit Phase

MOREHEAD STATE GROUND STATION MODIFICATIONS AND FURTHER ENHANCEMENTS

Interplanetary CubeSats will require communications, tracking, and navigation support that could exceed the current capacity of the Deep Space Network, especially if all desired tracking needs from each CubeSat mission are to be met. Even with the expansion of new antennas and with the implementation of new techniques to improve antenna utilization (i.e. multiple satellites per beam), new low-cost approaches to augment the DSN in support of the unfolding SmallSat revolution are needed.[15]

Toward that end, the MSU 21-m antenna system is being upgraded under the support of NASA's Advanced Exploration Services (AES) to be integrated into the DSN as an auxiliary station to support SmallSat missions. This MSU upgrade project serves as a test case to define a path for integration of other non-NASA ground stations to support SmallSat missions. The project focuses on the implementation of DSN capabilities, techniques and processes, including deep space ranging, navigation and tracking techniques and capabilities, the implementation of Space-link Extension (SLE) protocol, CCSDS data standardization, and asset scheduling capabilities.[16]

The ultimate deliverables of the two-year effort, to be completed in 2018, will be: 1.) DSN-compatible 21-m System Architecture Design that includes hardware and software upgrades necessary to provide deep space telemetry, tracking, and command functions compliant with the CCSDS SLE specifications; 2.) Demonstration of the MSU 21-m antenna as a DSN-compatible operational node; 3.) Demonstration of ground system capabilities in demodulating and decoding CubeSat telemetry data, accepting and transmitting commands to CubeSats, and providing Doppler and ranging data for CubeSat deep space navigation strategies and processes; and 4.) Compatibility with uplink and downlink processes implemented in NASA’s Advanced Multi-Mission Operations System (AMMOS).[17]

The process of upgrading a non-DSN asset to DSN compatibility has proven to be challenging. To support the 21-m upgrade, custom DSN-style equipment had to be developed. No commercial off-the-shelf (COTS) equipment exists; all tracking receivers, telemetry receivers, uplink transmitters, and data collection systems had to be developed. Additionally, Cesium and Rubidium atomic clocks and Global Positioning System (GPS) steered crystal oscillators do not have phase-noise characteristics necessary to support the desired radiometric accuracy for deep space missions at X-band. Morehead State will install a hydrogen MASER timing reference standard to meet the objectives. In the case of the 21-m, it was determined that the existing X-band feed was not adequate, the intermediate frequency (IF) processor system would have to be redesigned. Essentially all receiver, transmitter, tracking systems, data collection systems and network monitoring systems would have to be developed. In addition, the university's IT and physical security would have to be upgraded. While the challenges have been substantial, the DSN-JPL and Morehead State teams have competed the system architecture and have begun to build a "DSN-lite" version of the instrumentation. A system block diagram is shown in Figure 20.[18]

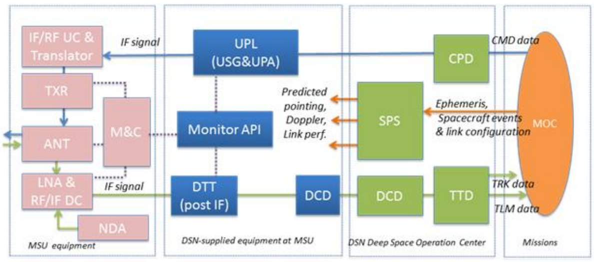


Figure 20: Block Diagram Overview of the Morehead State 21-m DSN Ground Station

The DSN-compatibility upgrade will result in a significant improvement in the performance of the MSU 21-m station. Current performance measures along with post upgrade targets are provided in Table 6. Major improvements that are being implemented to improve the existing system's performance include a high power capable X-band feed system that can accommodate a 1 KW power amplifier and accommodate an ultra-cool cryogenic low noise amplifier (LNA). The cryogenic LNA is one of the key enabling technologies associated with the significantly improved station performance. Closed-cycle (maintenance free without cryogenic compressors and plumbing), compact cryogenic LNAs have been identified (Callisto Technologies) that achieve a <20K noise temperature at X-band (7.25-8.5 GHz) through the use of innovative Sterling-cycle cryocoolers, liquid nitrogen (LN2)-fed cold fingers, compact compressors, and powdered aerogel insulation. Contactless bearings and seals are designed for ultra-long operating life (>10 years). This technology represents the capability to improve antenna G/T (approximately 5 dB/K at 8 GHz) and increase data transfer rates (up to 60%). These cryogenic LNAs, along with an optimized X-band feed, allow the upgraded system to achieve a significant performance improvement summarized in Table 6.

Table 6: Morehead State 21-m Station Performance Measure Pre- and Post-Upgrade Targets

Performance Measure	Current Values	Post-Upgraded Targets
X-Band Frequency Range	7.0 – 7.8 GHz	7.0 – 8.5 GHz
LNA Temperature	70 K	< 20 K
System Temperature Tsys	215 K	<100 K
Antenna Gain	62.0 dBi (@ 7.7 GHz)	62.7 dBi (@8.4 GHz)
System Noise Spectral Density	-175 dBm/Hz	<-178 dBm/Hz
G/T at 5° Elevation	37.5 dBi/K	40.4 dBi/K
Time Standard	GPS (40-ns)	MASER 3.3 E-14 over 100 secondspse)
SLE Compliant	No	Yes
CCSDS Capable	No	Yes

The 21-m DSN upgrade project will demonstrate a cost-effective solution for expanding DSN capabilities by utilizing non-NASA assets to provide significant support for CubeSat and MicroSat missions to the Moon, Earth-Sun Lagrange points, and Near Earth Asteroids. It is anticipated that the increasing volume of interplanetary research with small satellites will be supported by existing stations with upgraded performance, including larger-aperture NEN stations that will target providing services for mission critical post-deployment activities.

POTENTIAL NEN ENHANCEMENTS & THE BENEFITS FOR EM-1 CUBESAT MISSIONS

Potential NEN Enhancements

NEN offers high gain ground system solutions for lunar missions. NEN currently has apertures ranging from 4.7-m to 15-m worldwide, with the exception of an 18-m asset at White Sands. Additional 18-m+ apertures could be added to the NEN through commercial services. Furthermore, the NEN could add smaller apertures to the network, reducing utilization and freeing up availability on larger NEN assets, which could then be used for lunar missions.

Currently NEN Commercial stations at Hawaii and Dongara, Australia have X-band uplink capability and with some minor modification these stations could support EM-1 missions. Addition of a tunable up converter (to convert from 70 MHz to X-band frequency) and IF distribution system to send IF from the Cortex modem to the up converter are required.

Also, the control and monitor software needs to be updated for these new capabilities.

NASA NEN is considering adding X-band uplink capability to other NASA NEN stations. The main sub components, such as X band SSPAs, Subreflectors, Up Convertors and Receivers should to be upgraded.

In the present configuration, the NEN ground stations use two different models of Cortex Telemetry Tracking and Control (TT&C) that do not currently support the Turbo 1/6 encoding, sequential ranging, or PN ranging that the Lunar IceCube is planning to use in conjunction with the Iris transponder. Iris/DSN compatibility can be achieved by a non-intrusive firmware upgrade by Zodiac applied to one of the models currently in use, the Cortex CRT Quantum, which then will have the full enhanced capabilities of a deep space upgrade. This upgrade includes advanced feature such as Turbo (1/2, 1/3, 1/4, 1/6), PN code ranging, sequential ranging, third order phase-locked loop (PLL), etc. It is designed to operate at a different IF; an up/down-converter from 720MHz to 70MHz will also be necessary.

The current LNAs at some NEN stations are outdated. For example, the NEN Wallops station uses an LNA with ~86 degree Kelvin noise temperature. Newer and updated LNAs, such as cryogenic LNAs, could improve performance. Upgrading the 20-year old LNAs with new LNAs to improve the ground system G/T performance is potentially in consideration. The station G/T improvement will reduce the S/C transmitting power requirement for the S/C-to-ground communication downlink data rate for power-limited CubeSats.

NEN Enhancements Potential Benefits for EM-1 CubeSat Missions

Most of the EM-1 CubeSat missions will carry a JPL Iris transponder with 1/6 Turbo coding. In comparison to tradition CCSDS convolutional code, 1/6 Turbo code provides significant coding gain to reduce the CubeSat transmitting power requirement for the downlink data rate.

NEN potential Cortex enhancements with 1/6 Turbo code and sequential ranging/PN ranging will enable NEN station compatible with EM-1 CubeSats missions carrying the JPL Iris transponder.

Modification of X-band uplink at NASA commercial provider sites will enable uplink compatibility with the Iris transponder for command, Doppler and ranging requirements.

NEN station LNA enhancement will further reduce the CubeSat transmitting power requirement to support the downlink data rate. While the NEN is not anticipated to provide primary support to any of the thirteen EM-1 CubeSat missions, the NEN upgradeable ground system solutions for lunar, L1/L2, and future exploration CubeSat missions, could benefit the EM-1 CubeSat missions carrying an Iris transponder in the form of signal compatibility, coverage, and large beamwidth.

NASA-owned NEN and NEN commercial ground systems are positioned around the globe and are able to provide significant to full coverage, depending on sites utilized, for CubeSats in lunar orbit or beyond (e.g., L1/L2 missions). NEN coverage could be utilized to provide higher data rate support to EM-1 CubeSat missions immediately following dispersal from Orion (~35,000 km through 100,000km). Figure 21 illustrates NEN coverage to EM CubeSat missions at lunar distances with either three or four stations. Figure 22 illustrates four site NEN coverage to EM CubeSat missions at the approximate distance of Bus Stop #1, 25,000km, as well as the distance where NEN can begin to provide complete global coverage, 35,000km.

Smaller NEN apertures (e.g., 11-m), compared to other apertures, provide a larger beam width, which can benefit CubeSat missions in the event of navigation/ephemeris uncertainty. Figure 23 illustrates NEN beam width advantage for EM-1 lunar missions.

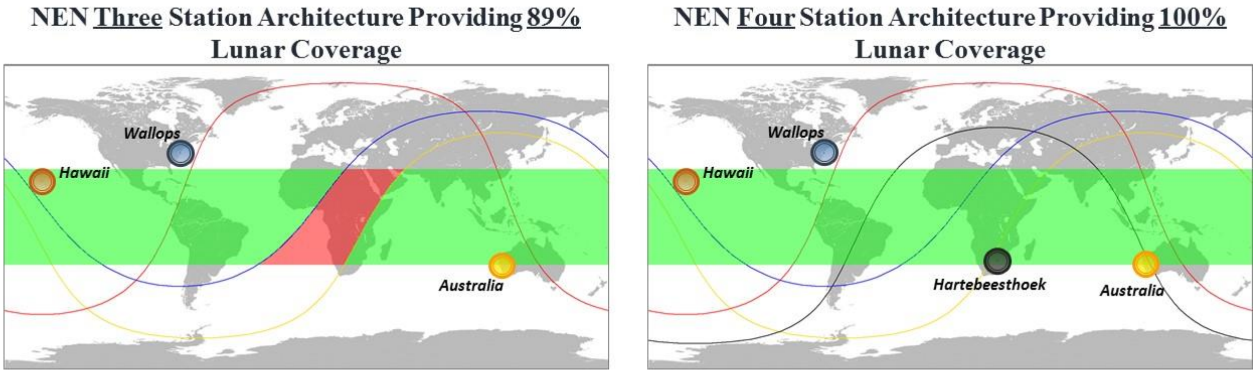


Figure 21: NEN Coverage for EM CubeSat Missions at Lunar Distances

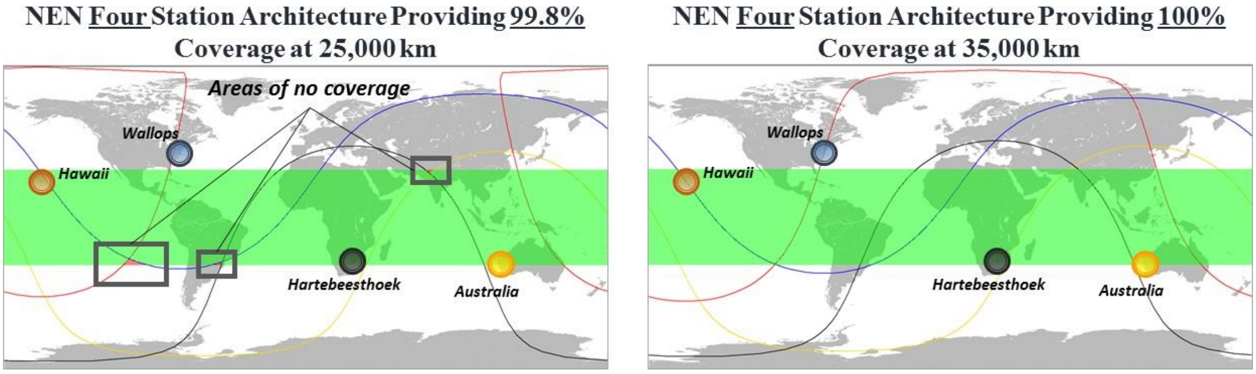
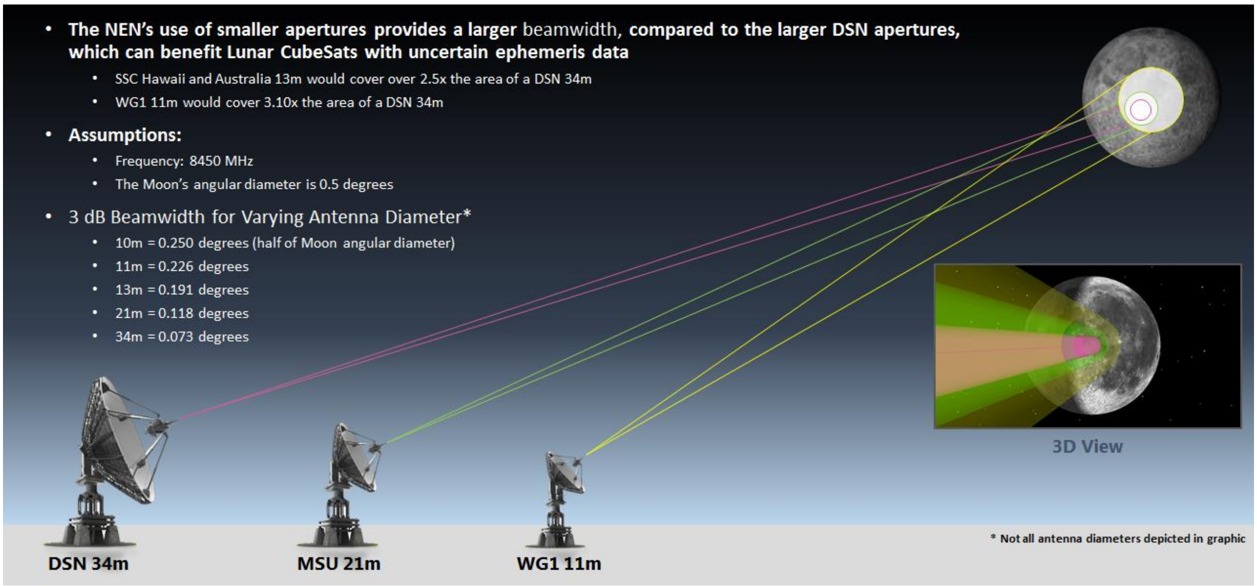


Figure 22: NEN Coverage for EM CubeSat Missions at Deployment Distances



- **The NEN's use of smaller apertures provides a larger** beamwidth, **compared to the larger DSN apertures, which can benefit Lunar CubeSats with uncertain ephemeris data**
  - SSC Hawaii and Australia 13m would cover over 2.5x the area of a DSN 34m
  - WG1 11m would cover 3.10x the area of a DSN 34m
- **Assumptions:**
  - Frequency: 8450 MHz
  - The Moon's angular diameter is 0.5 degrees
- 3 dB Beamwidth for Varying Antenna Diameter*
  - 10m = 0.250 degrees (half of Moon angular diameter)
  - 11m = 0.226 degrees
  - 13m = 0.191 degrees
  - 21m = 0.118 degrees
  - 34m = 0.073 degrees

* Not all antenna diameters depicted in graphic

Figure 23 Aperture Size to Beamwidth Illustration

NEN LUNAR AND L1/L2 SUPPORT WITHOUT ANY ENHANCEMENT

Currently, NEN NASA owned and commercial stations support S, X and Ka frequency bands. The station Cortex modem is capable of supporting a variety of modulation and coding schemes, including power and bandwidth efficient low-density parity-check (LDPC) code. As shown in Table 1, there are COTS S- and X-band Software Designed Radio (SDR) radios that could be used by CubeSats in lunar and L1/L2 orbit. Although a majority of the EM-1 CubeSats will use the Iris transponder with Turbo coding, and while the current NEN Cortex modems do not support Turbo coding without a license upgrade, NEN is capable, without any enhancements, of supporting CubeSats using COTS radios in lunar and L1/L2 orbit. NEN station S-band uplink can be used today to support CubeSat commanding. There are tradeoffs that can be accomplished between CubeSat transmitting power and signal design, for instance Turbo vs LDPC coding, to achieve the desired downlink data rate.

NASA NEN INITIATIVE FOR BETTER SUPPORT OF CUBESAT COMMUNITY

In addition to enhancement of ground stations, the NASA NEN is focusing on multiple initiatives to meet the future needs of the CubeSat community.

NASA missions can obtain NEN ground station services on NASA-owned antennas for free. Today, NEN is also an effective broker for commercial services for NASA missions. The NEN is constantly on the lookout for new ground station services which may offer lower costs and greater coverage.

NASA missions do need to pay for Mission Planning, Integration and Test including compatibility testing and end-to-end testing. The NEN and the Goddard Space Flight Center Networks Integration Management Office (NIMO) recently completed a Lean Six Sigma Project to explore reducing the cost of compatibility testing for CubeSat missions. The Project resulted in finding cost savings totaling greater than 60%.

Currently, the NEN schedules for about 40 missions using NASA and commercial sites. Scheduling is another area that will require streamlining as the number of missions increases. The goal is to handle the increased complexity of constellations of CubeSats without increasing NEN scheduling staff.

CONCLUSION

Because of the lower cost, opportunity for simultaneous multipoint observations, it is inevitable that CubeSats will continue to increase in popularity for not only LEO missions, but for lunar and L1/L2 missions as well. The challenges for lunar and L1/L2 missions for communication and navigation are much greater than for LEO missions, but are not insurmountable. Advancements in flight hardware and ground infrastructure will ease the burden.

> *The NEN is ready today to support lunar and L1/L2 CubeSats. Potential enhancements to both Morehead State University and NEN ground stations will increase the science return from CubeSats and traditional non-CubeSat missions. A relatively small investment in ground equipment could payoff over tens or hundreds of future missions.*

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