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

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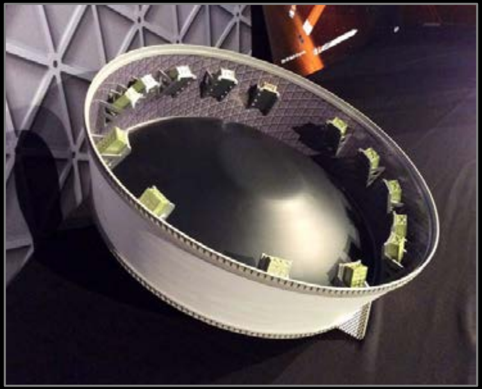
# EM-1 CubeSats & Lunar IceCube Mission Overview

- **NASA's EM-1 will be the maiden voyage of the Space Launch System (SLS), ushering NASA into a new era of solar system exploration**
  - SLS, supporting human exploration beyond Low Earth Orbit (LEO), will also serve as a platform to launch small satellites flying onboard as secondary payloads
  - EM-1 will launch thirteen CubeSats that will perform science investigations that address NASA Strategic Knowledge Gaps
  - CubeSat missions will also demonstrate a variety of enabling technologies, including communication and ranging



*Secondary CubeSat payloads on the adapter between the SLS upper stage and the Orion spacecraft*

- **Lunar IceCube will be one of the CubeSats to be launched from EM-1**
  - Lunar IceCube is a partnership between Morehead State University (MSU), GSFC, JPL, the Busek Company, and Vermont Technical College
  - Lunar IceCube will prospect for water in solid, liquid, and vapor forms and other lunar volatiles from a ~100 km lunar orbit
  - Lunar IceCube will be deployed by the SLS at Bus Stop One, at a distance of approximately 25,000km

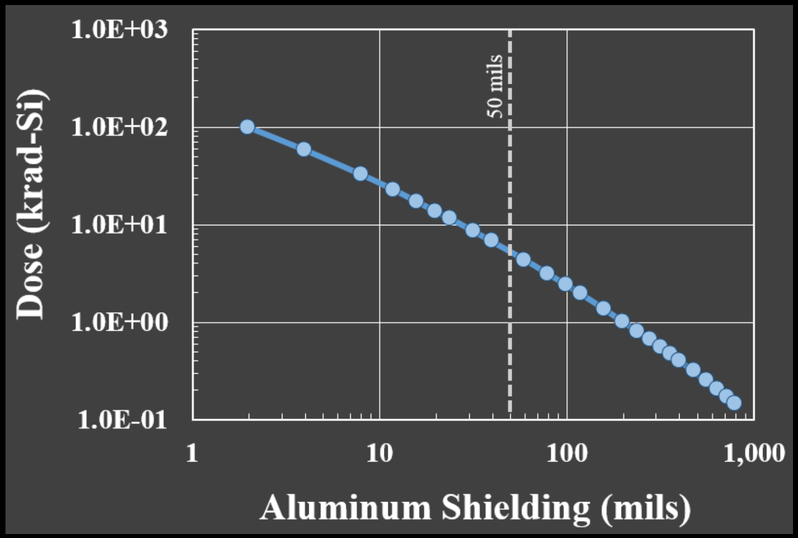
*Lunar CubeSat Spacecraft*

# Lunar IceCube: Communication & Navigation Needs

- **Lunar IceCube navigation and communication poses challenges:**
  - Precise orbit determination after deployment is required for lunar flyby maneuver planning
  - Establishing communication links given limited onboard power
- **To meet these challenges a large aperture on the ground is required**
  - DSN will be the primary network
  - MSU will manage ground operations for all phases and utilize their 21-m antenna to provide significant gain and link margin
  - The NEN, as a significant addition, can provide comprehensive tracking and telemetry services from facilities around the globe
- **Lunar IceCube navigation will be performed by the GSFC Flight Dynamics Facility (FDF)**
  - GSFC will provide navigation and maneuver planning
  - FDF will provide planning, ephemeris generation, tracking evaluation, operational products, and data archiving
- **Required tracking data and related accuracies vary over the transfer trajectory**
  - Frequency of tracking will vary from every opportunity to ever few days depending on the phase of the mission
  - Navigation accuracies of <100 m in position and <0.1 cm/s in velocity are required

# Lunar IceCube: Radiation Requirements

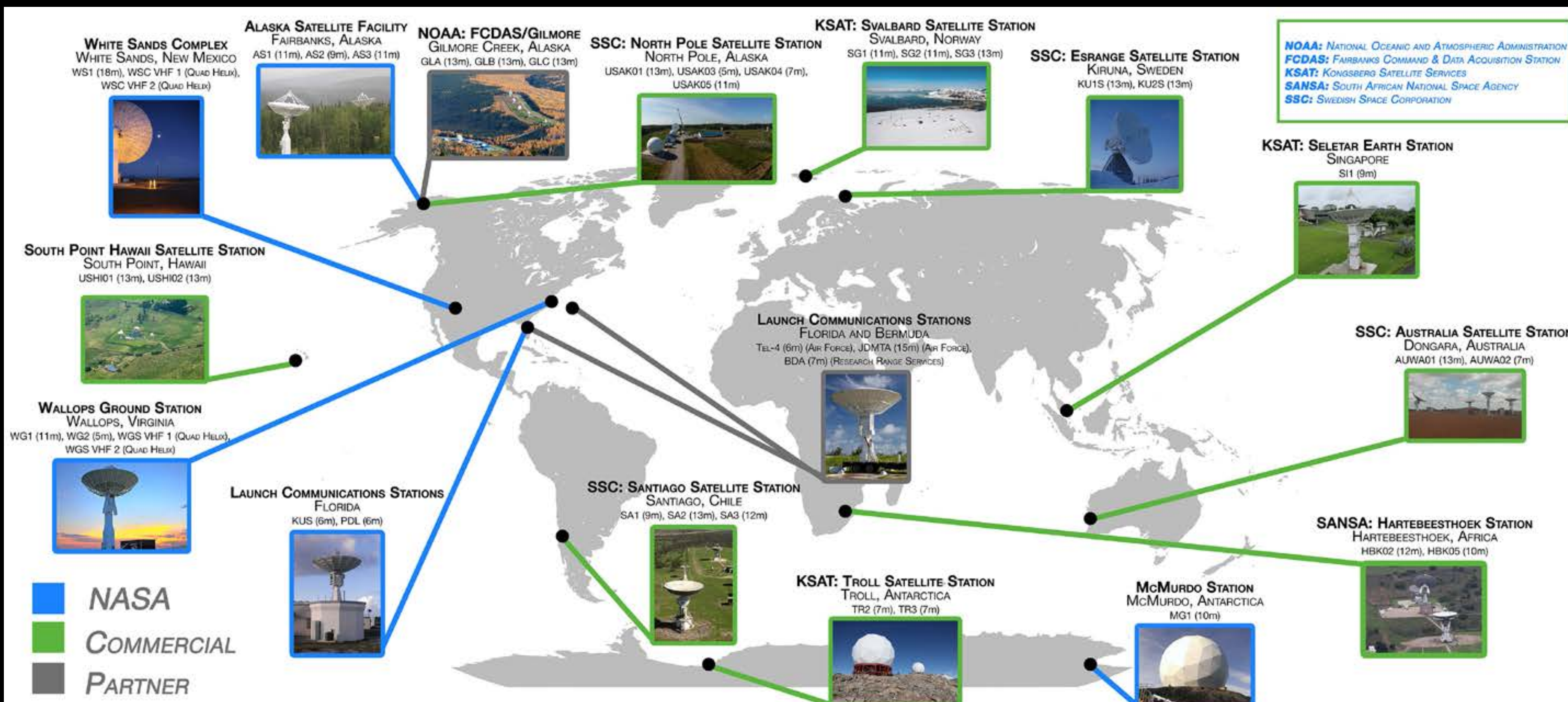
- **GSFC radiation branch performed an analysis for Lunar IceCube**
  - The radiation environment is harsh from a Galactic (Heavy Ion) Radiation perspective
  - Trips through the Van Allen belts early in the mission will expose Lunar IceCube to Total Ionizing Dose (TID) Radiation
- **Lunar Ice Cube Radiation Tolerance Requirements:**
  - 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.)
  - DRE EEE Parts shall meet LETth of > 75 MeV-cm2/mg for potential destructive events (SEL, SEB, SEGR, etc.)
  - DRE EEE Parts shall meet 5 krads (Si) Total Ionizing Dose (TID) assuming 50 mils Al shielding




*Lunar IceCube Dose – Depth at 95% Confidence*

# NASA Near Earth Network Project Overview

Near Earth Network (NEN) is composed of stations distributed throughout the world. The NEN supports orbits in the Near Earth region from Earth to 2 million kilometers



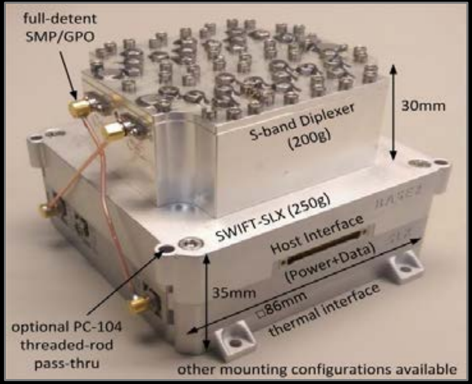
# Sample CubeSat Radios For Lunar and L1/L2 Missions

| Freq. | Vendor / Name | Size (cm) | Mass (g) | Flight Heritage | Max Data Rate | NASA Network Compatibility* |
|---|---|---|---|---|---|---|
| S-Band | Innoflight / SCR-100 | 8.2x8.2x3.2 | 300 | Sense NanoSat | 4.5 Mbps Tx | NEN, SN, DSN |
| | Tethers Unlimited / SWIFT-SLX | 10x10x3.5 | 380 | None | 15 Mbps Tx | NEN, SN, DSN |
| | Clyde Space / S-Band TX (STX) | 9.6x9.0x1.6 | < 80 | UKube-1 | 2 Mbps Tx | Partially NEN |
| | Microhard / MHX-2420 | 8.9x5.3x1.8 | 75 | RAX | 230 kbps Tx<br>115 kbps Rx | Partially NEN |
| | Quasonix / nano TX | 3.3x3.3x3.3 | <200 | CPOD | 46 Mbps Tx | NEN |
| X-Band | LASP & GSFC / X-band Radio | 9.8x9x2 | 500 | None | 12.5 Mbps Tx<br>50 kbps Rx | NEN |
| | Syrlinks / X-band Transmitter | 9x9.6x2.4 | 225 | None | 5 Mbps Tx | NEN |
| | Marshall / X-band Tx | 10.8x10.8x7.6 | <1000 | FASTSat2 | 150 Mbps Tx<br>50 kbps Rx | NEN |
| | Tethers Unlimited / SWIFT-XTS | 8.6x4.5 (0.375U) | 500 | None | 300 Mbps Tx | NEN, SN, DSN |
| | JPL / Iris Transponder | 0.4U | 400 | INSPIRE | 256 kbps Tx<br>8 kbps Rx | DSN, Partially NEN |
| Ka-Band | Canopus Systems / Ames Ka-band Tx | 18x10x8.5 | 820 | None | 125 Mbps Tx | NEN, SN, DSN |
| | Tethers Unlimited / SWIFT-KTX | 8.6x4.5 (0.375U) | 500 | None | 300 Mbps Tx | NEN, SN, DSN |

** Compatibility shown as advertised by vendor and needs to be verified at GSFC Compatibility Test Laboratory (CTL)*

*Innoflight SCR-100*


*Quasonix S- Band Transmitter*



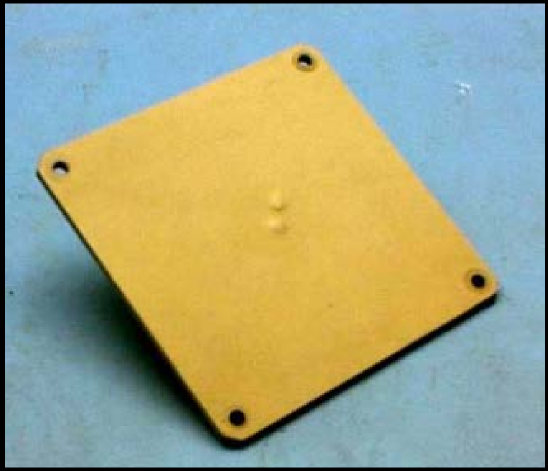

*Tethers Unlimited SWIFT-SLX*

# Sample CubeSat Antennas For Lunar and L1/L2 Missions

| Antenna Vendor | Antenna Type | Band | Antenna Gain (dBi) | Dimensions | Mass (g) |
|---|---|---|---|---|---|
| **Antenna Development Corporation** | Low-Gain Patch Antenna (LGA) | S | 2 | (4 x 4x0.25)" | 115 |
| **Haigh Farr S-band Patch** | Patch | S | 2 | (94x76x4) mm | 62 |
| **University of Southern California's Information Sciences Institute Space Engineering Research Center (SERC)** | Deployable High Gain Antenna | S/X | >24 | 50 cm | 760 |
| **BDS Phantom Works** | Deployable High Gain Antenna | S | 18 | 50 cm | 1000 |
| **Antenna Development Corporation** | Patch | X | 9 | (1.85x1.85x0.55)" | 300 |
| **BDS Phantom Works Deployable High Gain X-band Antenna** | Deployable High Gain Antenna | X | 25 | 50 cm | 1000 |
| **Canopus System Horn** | Horn | Ka | 25 | 18 cm | 820 |

** Specifications shown as advertised by vendor*

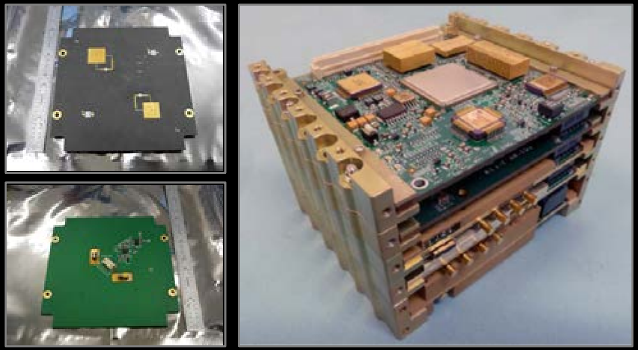
*University of Southern California's Information Sciences Institute Space Engineering Research Center (SERC)*



*Ant Dev. Corp: Medium Gain X-band Patch Array Antenna*

# Lunar IceCube Communication System / Iris Transponder

- **Lunar IceCube communication system consists of:**
  - 4 custom design X-band patch antennas
  - Iris transponder without a diplexer
- **Patch Antenna performance characteristics:**
  - Receive Band: 7.145-7.190 GHz
  - Transmit Band: 8.400-8.450 GHZ
  - Gain: 6 dBi
- **Iris transponder features:**
  - Modular design allows user to select layers necessary to meet needs, be it S-band, X-band, Tx, Rx
  - The transponder is radiation tolerant up to 15 Krads and its memory modules are all radiation tolerant
- **Iris transponder features continued:**
  - Switchable discrete data rates
    - Telemetry rates ranging from 62.5 bps up to 256 kbps; Lunar IceCube is exploring telemetry data rates of 16, 32, 64, 128 kbps
    - Command rates ranging from 62.5 bps up to 8 kbps, in powers of two
  - Lunar IceCube plans to use the power efficient Turbo 1/6 code



*Patch antennas and Iris transponder*

# Lunar IceCube NASA NEN Ground Station Coverage

- **DSN/MSU will provide prime support to Lunar IceCube during all phases, but the NEN would be able to provide additional comprehensive support**
  - MSU has visibility for the 8-hour event following deployment, but not for the next three cruise events
  - DSN/MSU will have lengthy periods where only one site has coverage
- **As a significant addition, the NEN could ensure a minimum of two sites in view at all times and provide supplemental and backup support**
- **Based on current NEN locations, four X-band capable equatorial sites would be required to provide full global coverage to Lunar IceCube based on its trajectory**
  - The commercial sites SSC Hawaii and Australia are the only NEN stations currently capable of X-band uplink and would be ideal due to their larger antennas (13-m) and equatorial location
  - The NASA owned Wallops site has an 11-m X-band system and is located to complement the coverage provided by the Hawaii and Australia sites
  - The addition of the commercial site in Hartebeesthoek, South Africa, which has a 10-m system, would ensure full global coverage
  - Note: Sites would require modification for Lunar IceCube compatibility

# Achievable Ranging and Data Rates

- **Lunar IceCube had considered the use of either sequential tone ranging or Pseudo-Noise (PN) ranging, but has decided to use sequential ranging**
- **Lunar IceCube implementation of sequential ranging will use two modes for uplink and one mode for downlink**
  - Ranging data channel having a major tone for uplink
  - Command data channel modulating a subcarrier
  - A single tone ranging channel directly phase modulating the RF carrier for downlink

- **A NEN link analysis was performed to evaluate NEN X-band support for Lunar IceCube science data downlink**
  - Achievable data rate will vary depending on the distance to the Earth during different phases

**NEN Achievable Data Rates at a Range of 400,000 km**

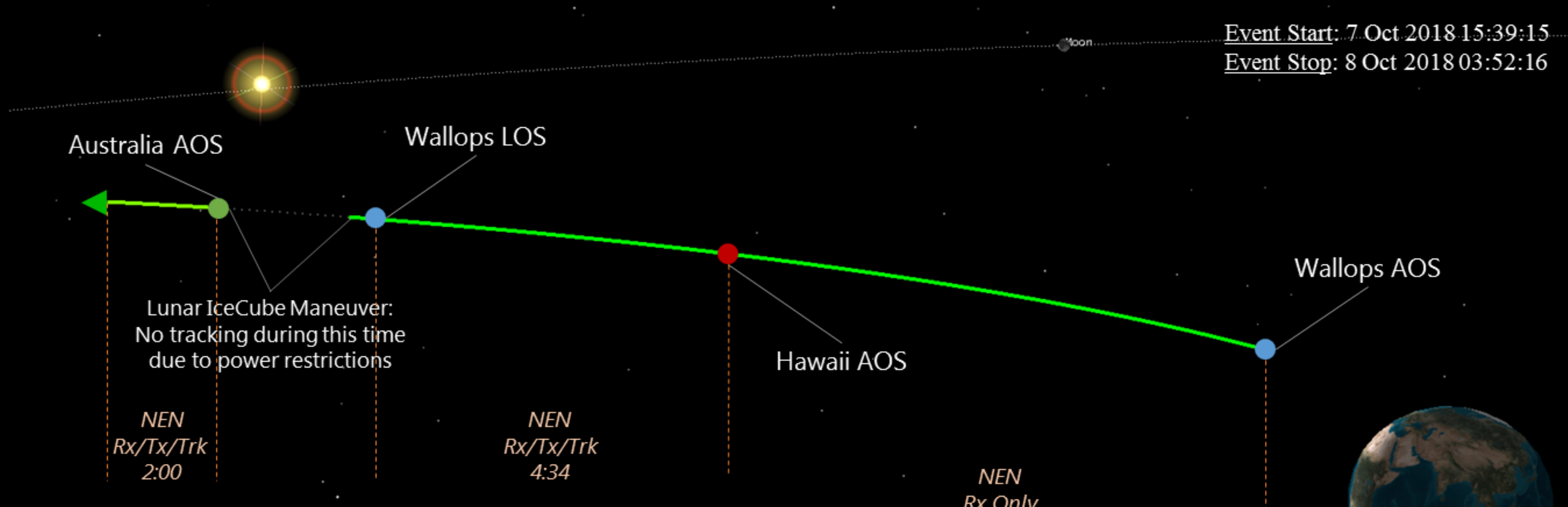
| Station | X-band G/T (dB/K)* | Achievable Rate |
|---|---|---|
| **Wallops** | 35.4 | 16 kbps |
| **Australia** | 37.7 | 32 kbps |
| **Hawaii** | 37.7 | 32 kbps |
| **Hartebeesthoek** | 30.5 | 8 kbps |

* Clear sky and 10° elevation angle

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

# NEN Coverage During Lunar IceCube Deployment Phase - Video

# NEN Coverage During Lunar IceCube Deployment Phase



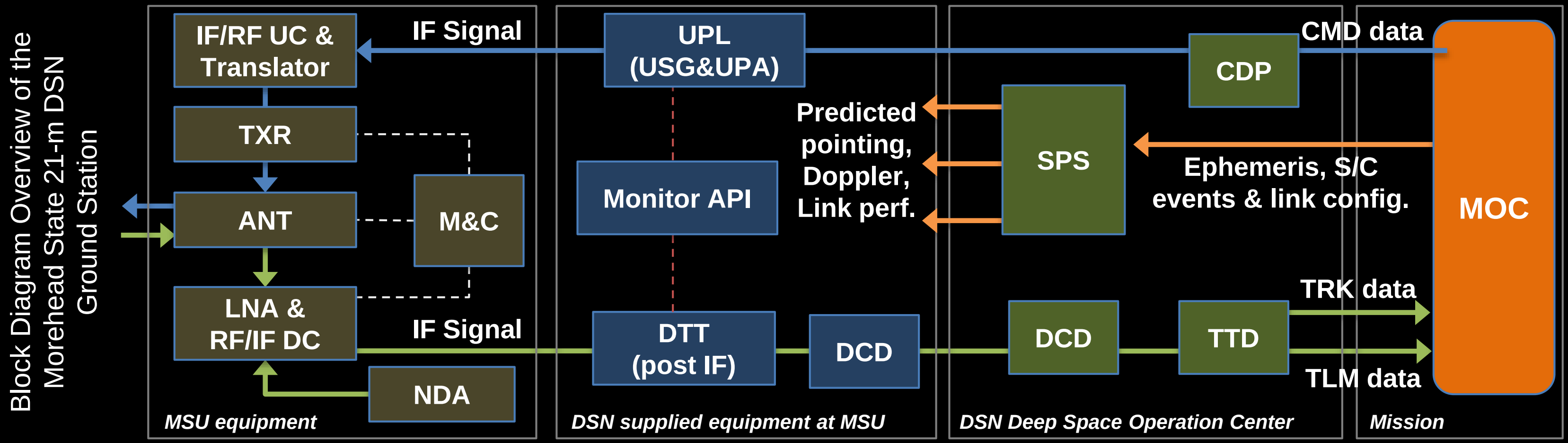

| Site | Max Range | Achievable Rate |
|---|---|---|
| Hawaii | 136,626 km | 256 kbps |
| Australia | 137,318 km | 256 kbps |
| Wallops | 109,643 km | 128 kbps |
| Hart. | - | - |

| 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: Coverage times are based on line of site coverage and do not guarantee commitment of asset(s) for service. 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.

# Morehead State Ground Station Modifications and Further Enhancements

- **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 ground stations to support SmallSat missions
- **The ultimate deliverables of the two-year effort, to be completed in 2018, will be:**
  1. Design that includes hardware and software upgrades necessary to provide deep space telemetry, tracking, and command functions compliant with 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
  4. Compatibility with uplink and downlink processes implemented in NASA's Advanced Multi-Mission Operations System (AMMOS)



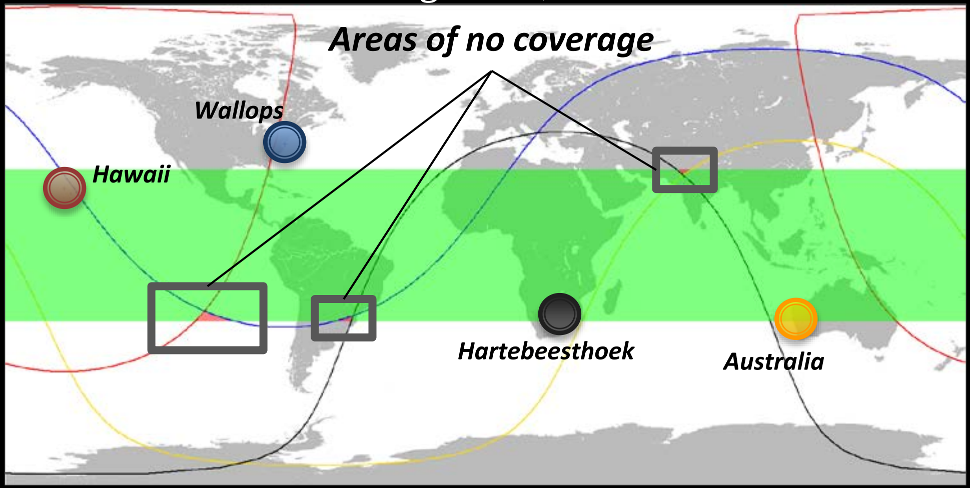
# Potential NEN Enhancements and Benefits

- **NEN commercial stations at Hawaii and Dongara, Australia have X-band uplink capability that could support EM-1 missions with some minor modifications to these stations**
  - Addition of a tunable up converter and IF distribution system between the Cortex modem and the up converter
- **NEN is considering adding X-band uplink capability to other NASA NEN stations**
  - **Addition of X-band uplink will help with frequency crowding in S-band**
- **NEN Cortex modem enhancements with 1/6 Turbo code and sequential ranging/PN ranging for compatibility with EM-1 CubeSats missions carrying the Iris transponder is potentially under consideration**
- **NEN ground system enhancements to achieve compatibility with missions carrying an Iris transponder would enable benefits in the form of coverage and larger beamwidth**

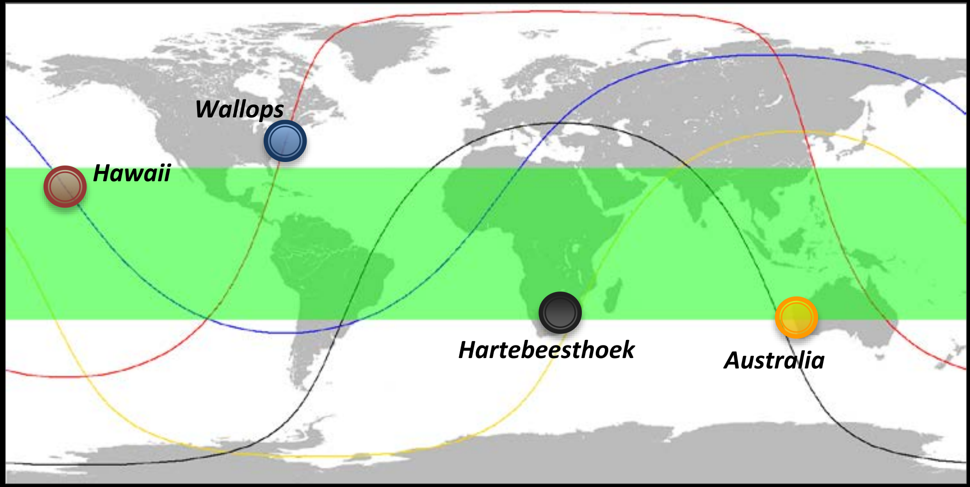
# NEN Benefits For EM-1 CubeSat Missions: Coverage

- **NEN NASA-owned and commercial ground systems are positioned around the globe and are able to provide significant to full coverage to CubeSats in lunar orbit or beyond**
  - Four select NEN stations could provide ~99.8% coverage at 25,000 km, the approximate distance where Lunar IceCube will separate
  - Full coverage, 100%, could be achievable at ~35,000 km and beyond, assuming four stations

**NEN Four Station Architecture Providing 99.8% Coverage at 25,000 km**

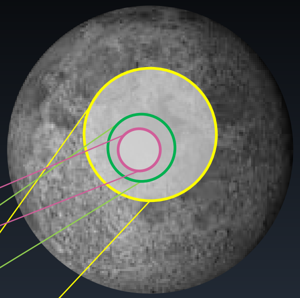


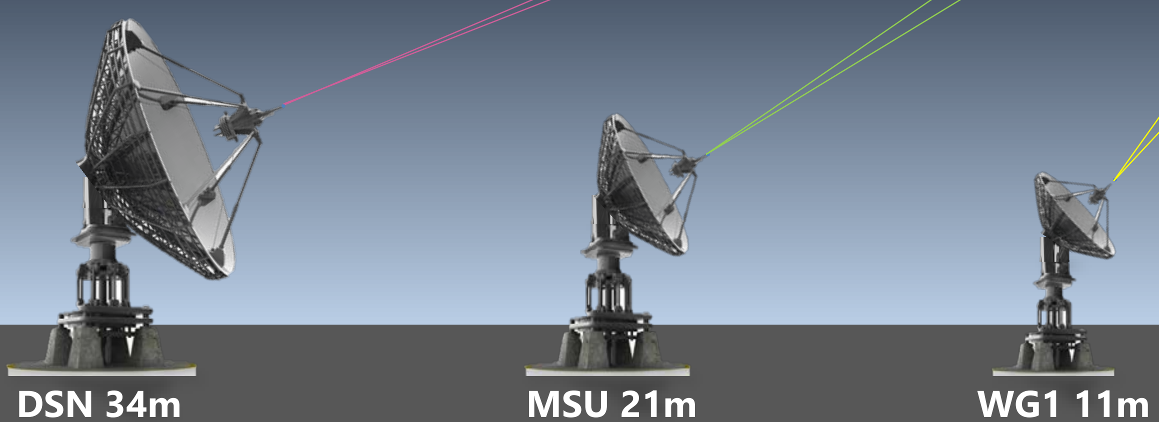

**NEN Four Station Architecture Providing 100% Coverage at 35,000 km and beyond**

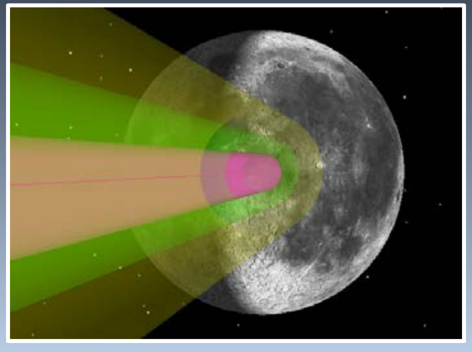


# NEN Benefits For EM-1 CubeSat Missions: Beamwidth

- **The NEN's use of smaller apertures provides a larger beamwidth, compared to larger apertures, which could 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**

# NEN Lunar And L1/L2 Support Without Any Enhancement

- NEN NASA owned and commercial stations support S, X and Ka frequency bands
- The station Cortex modem supports a variety of modulation and coding schemes, including power and bandwidth efficient low-density parity-check (LDPC) code, but requires a license upgrade for Turbo coding
- A majority of the EM-1 CubeSats will use the Iris transponder with Turbo coding
- COTS S- and X-band Software Designed Radio (SDR) radios are available for use by CubeSats in lunar and L1/L2 orbit
- NEN is capable, without any enhancements, of supporting CubeSats using COTS radios in lunar and L1/L2 orbit and current Cortex modems
- Tradeoffs can be accomplished between CubeSat transmitting power and signal design, for instance Turbo vs LDPC coding, to achieve the desired downlink data rate
- NEN station S-band uplink can be used today to support CubeSat commanding

# NASA NEN Initiatives For Better Support Of CubeSat Community

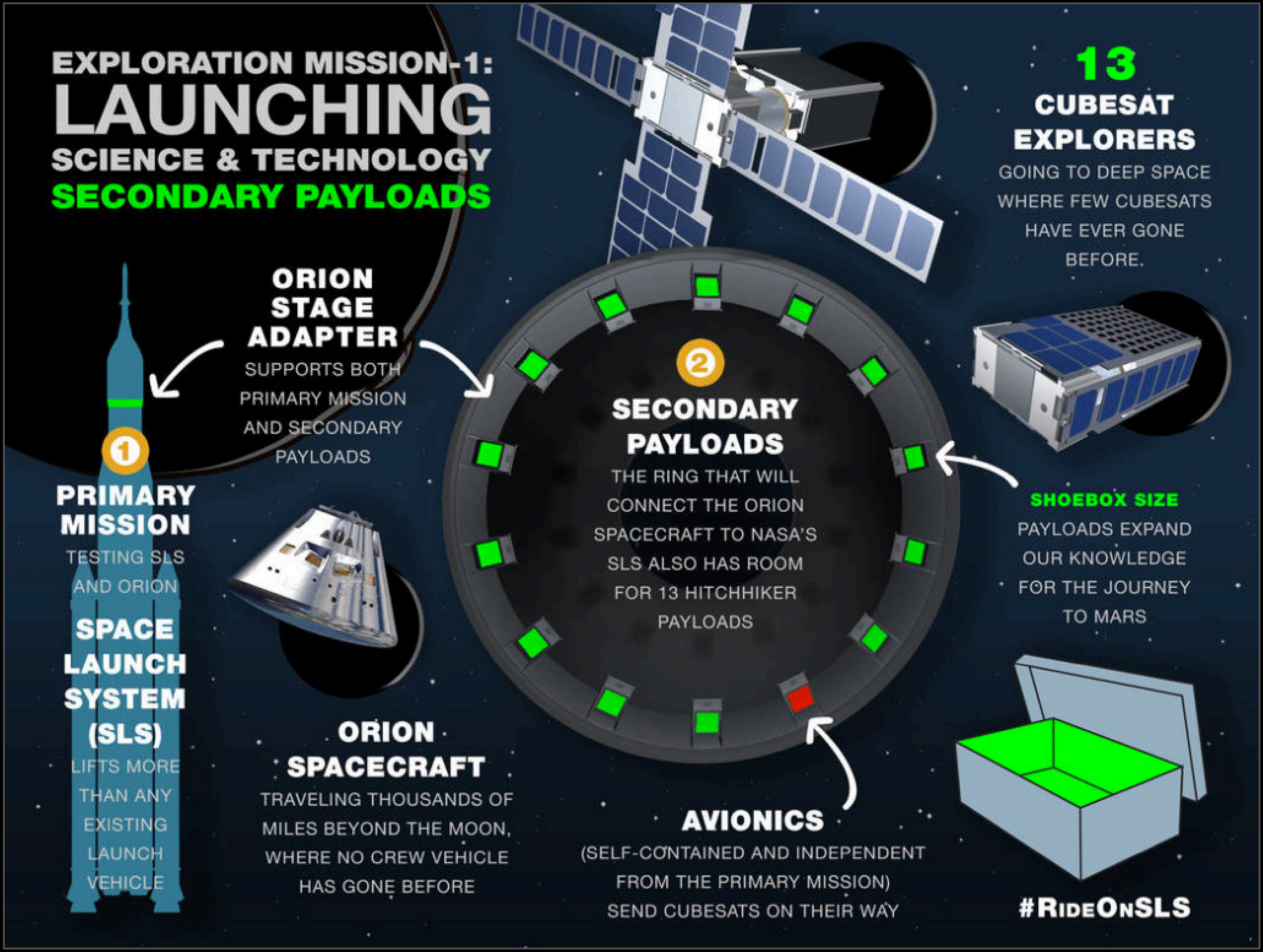
- **In addition to enhancement of ground stations, the NEN is focusing multiple initiatives to meet future needs of the CubeSat community**
  - NASA missions can obtain services on NASA-owned antennas for free
  - NEN can broker commercial services for NASA missions
  - NEN is investigating partnering with other agencies/universities to integrate new antennas into the NEN that may offer lower costs and greater coverage
- **NASA missions are required to pay for mission planning, integration, and testing (MPI&T), including compatibility and end-to-end testing**
  - NEN and GSFC Network Integration Management Office (NIMO) completed a Lean Six Sigma Project that explored ways to reduce MPI&T costs
  - The project identified savings that could total 60%
- **NEN is also investigating ways to streamline NEN scheduling**
  - As the number of missions increase, so does complexity
  - NEN is investigating ways to handle the increased load without increasing scheduling staff

# Conclusion

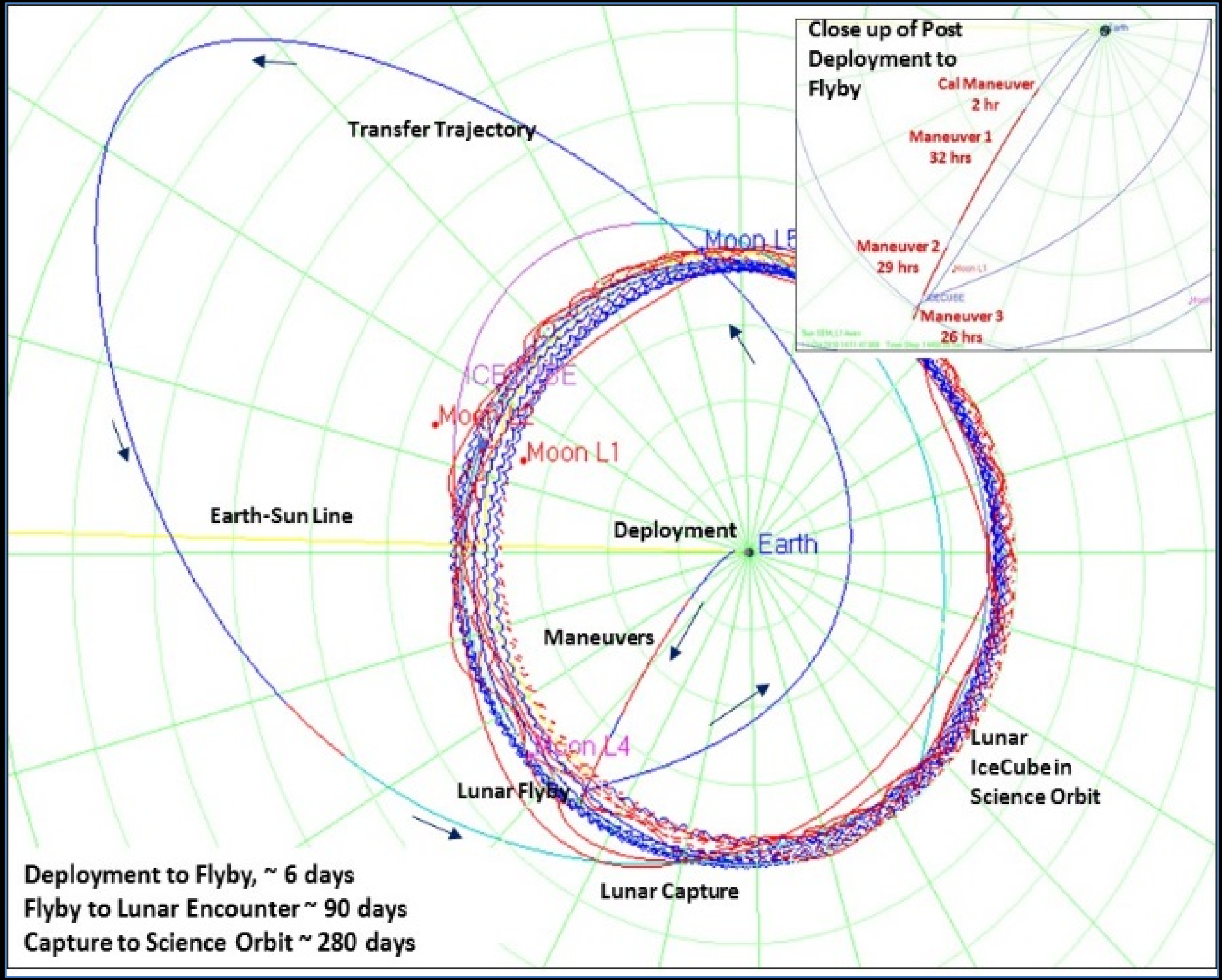
- The NEN is ready today to support lunar and L1/L2 CubeSats
- Potential enhancements to Morehead State University and NEN ground stations will increase the science return from CubeSats and traditional non-CubeSat missions
- A relatively small upgrade in NEN ground station equipment could payoff over tens or hundreds of future missions
- Advancements in flight hardware will also increase data rates and science return
- The challenges for lunar and L1/L2 missions for communication and navigation are much greater than for LEO missions, but are not insurmountable
- NEN ground systems could benefit lunar and L1/L2 CubeSat missions, including the EM-1 CubeSat missions

# BACKUP

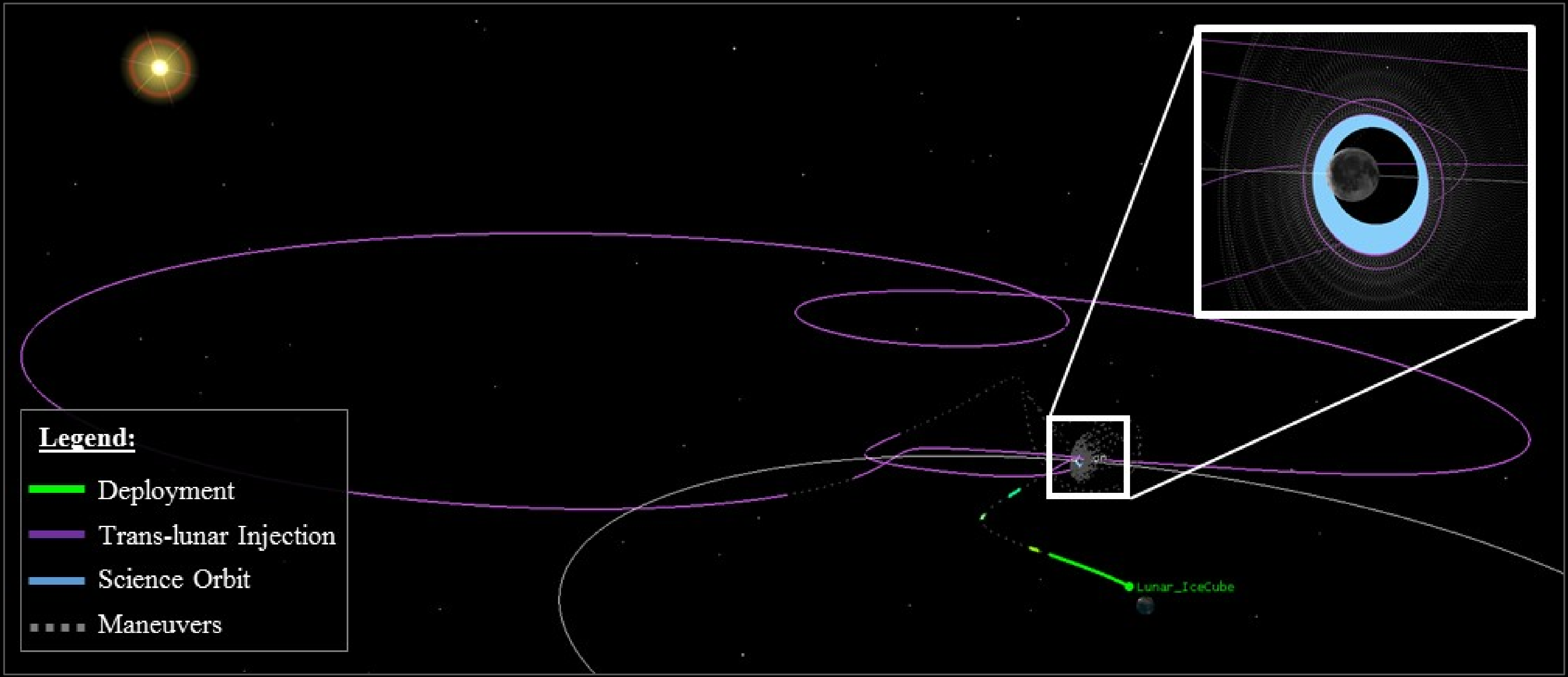
# EM-1 Secondary Payloads



# Lunar Ice Cube Mission Design

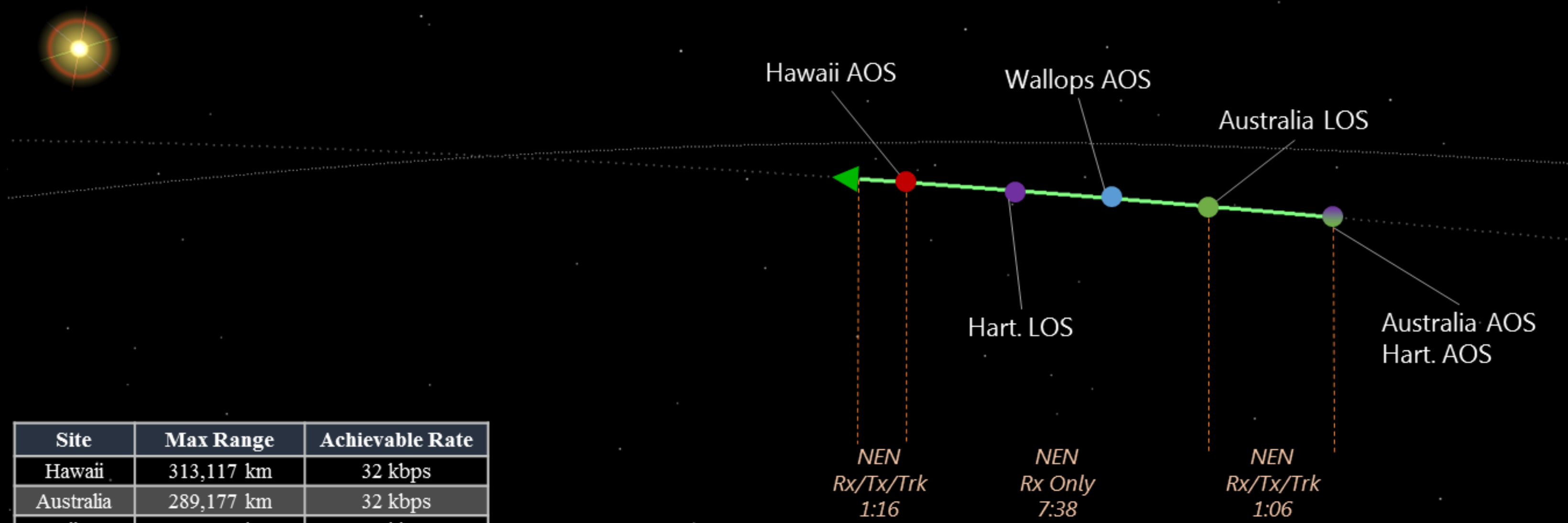


# Lunar IceCube Trajectory



# NEN Coverage During Lunar IceCube Deployment Phase #3

Event Start: 9 Oct 2018 11:56:19
Event Stop: 9 Oct 2018 21:56:19



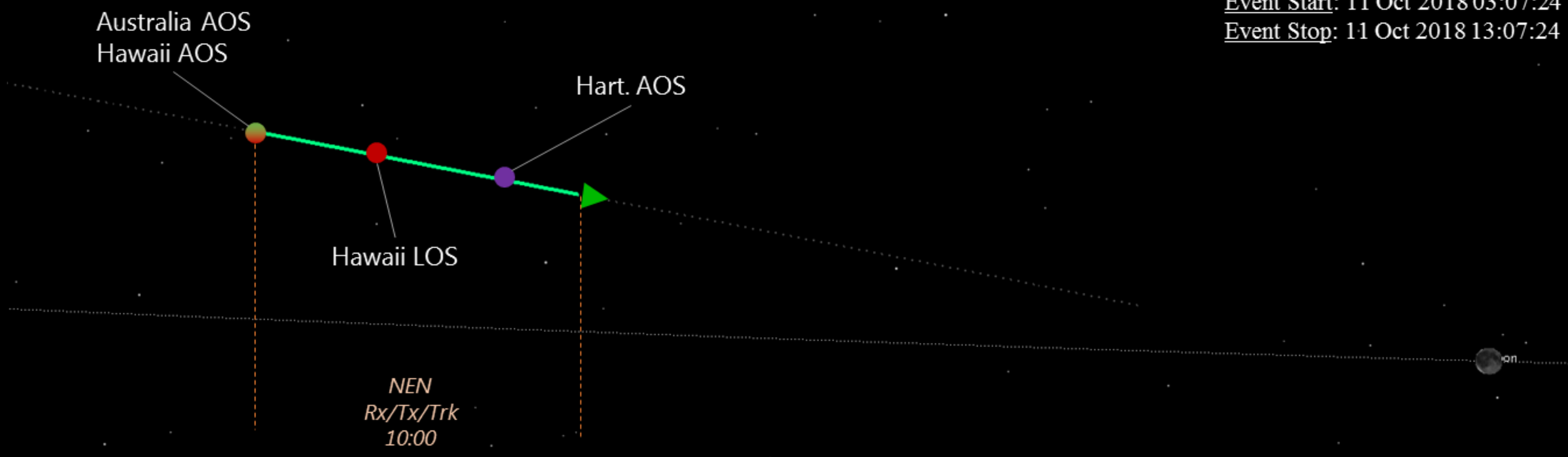

| Site | Max Range | Achievable Rate |
|---|---|---|
| Hawaii | 313,117 km | 32 kbps |
| Australia | 289,177 km | 32 kbps |
| Wallops | 312,716 km | 16 kbps |
| Hart. | 306,545 km | 8 kbps |

| 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: Coverage times are based on line of site coverage and do not guarantee commitment of asset(s) for service. 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.

# NEN Coverage During Lunar IceCube Deployment Phase #4

Event Start: 11 Oct 2018 03:07:24
Event Stop: 11 Oct 2018 13:07:24

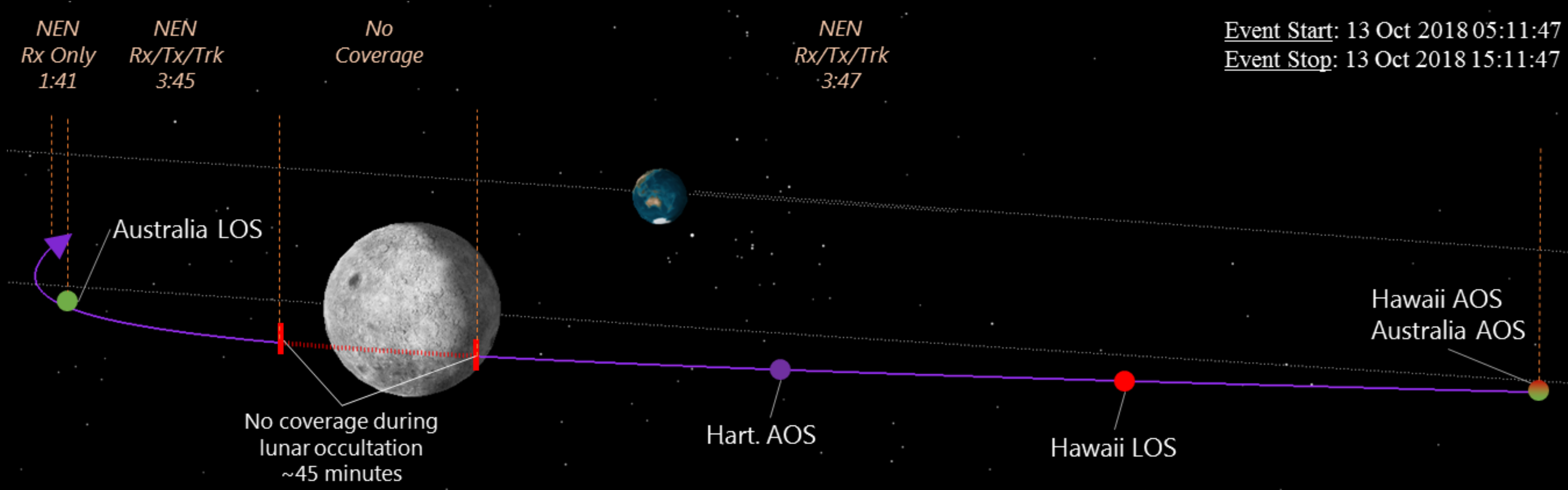



| Site | Max Range | Achievable Rate |
|---|---|---|
| Hawaii | 378,162 km | 32 kbps |
| Australia | 385,862 km | 32 kbps |
| Wallops | - | - |
| Hart. | 381,111 km | 4 kbps |

| 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: Coverage times are based on line of site coverage and do not guarantee commitment of asset(s) for service. 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.

# NEN Coverage During Lunar IceCube Outbound Lunar Flyby

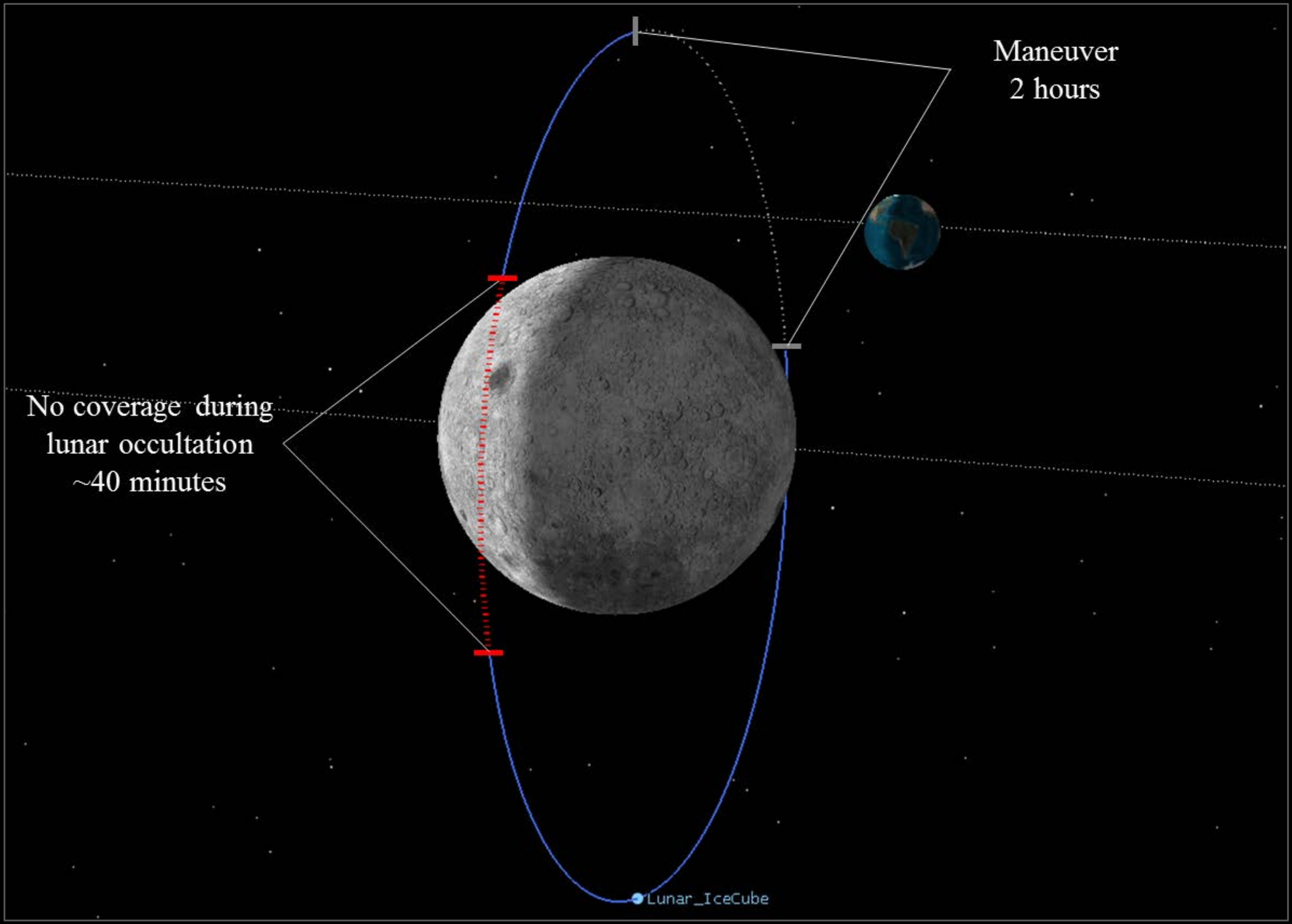



| Site | Max Range | Achievable Rate |
|---|---|---|
| Hawaii | 401,505 km | 32 kbps |
| Australia | 398,211 km | 32 kbps |
| Wallops | - | - |
| Hart. | 400,463 km | 4 kbps |

| 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 |

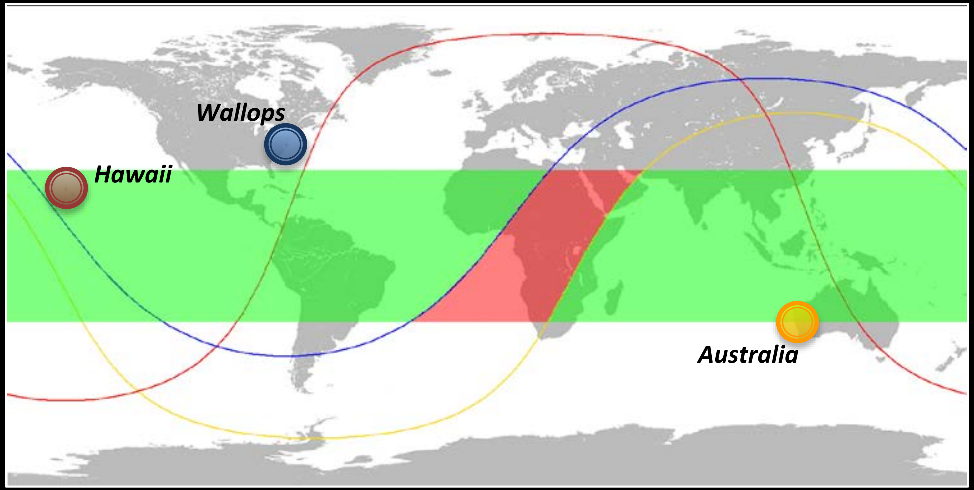
Note: Coverage times are based on line of site coverage and do not guarantee commitment of asset(s) for service. All NEN coverage times assume a 10 degree minimum elevation for RX, Tx, and Trk. DSN/MSU assumes a 6 degree minimum elevation for Rx and a 10 degree minimum elevation for Tx and Trk.

# NEN Coverage During Lunar IceCube Science Phase

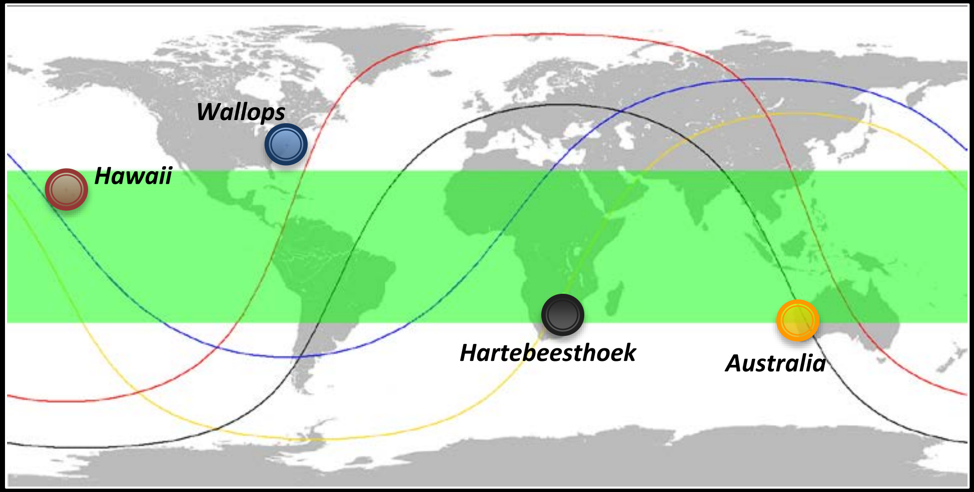


# NEN Coverage at Lunar Distances

**NEN Three Station Architecture Providing 89% Lunar Coverage**




**NEN Four Station Architecture Providing 100% Lunar Coverage**



# 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 |