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# DEVELOPMENT OF TELECOMMUNICATIONS SYSTEMS AND GROUND SUPPORT FOR EM-1 INTERPLANETARY CUBESATS MISSIONS: LUNAR ICECUBE AND LUNAH-MAP

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CubeSats are now providing an innovative way to explore space: they can be built by smaller teams in academic environments, and they generally require smaller budget than traditional missions. For this reason, a new trend has emerged in the last five years: interplanetary CubeSats.

Interplanetary CubeSats take advantage of the CubeSat paradigm and of the availability of commercial components developed for Low Earth Orbit (LEO) missions, but they are specifically designed to explore deep space. As a result, interplanetary CubeSats are essentially very different from Low Earth Orbit CubeSats in at least three technological areas: propulsion, radiation tolerance and telecommunication.

This paper is focused on telecommunication issues for interplanetary CubeSats which face harsher environments, longer path distances and have more navigation needs than the LEO CubeSats. For this reason, the design of telecommunication systems for interplanetary missions is extremely challenging and significant development is currently ongoing in the areas of radio design, antenna design and the design of ground support architectures.

This presentation focuses on the design of the telecommunication and ground support systems for two of the interplanetary CubeSats missions that will be launched on NASA's Space Launch System (SLS) Exploration Mission-1 (EM-1): Lunar IceCube and LunaH-Map. Given the commonalities between these missions, an effort is underway at JPL to develop a common set of telecommunication hardware systems to fit the envelope of the two missions' goals. Additionally, Lunar IceCube and LunaH-Map will also share the use of the Deep Space Network antennas and of the Morehead State University 21 m station, which is currently being upgraded especially for this purpose.

This presentation will provide a quick overview of the missions (including goals and telecommunication requirements) and it will also focus on the development of the telecommunication systems design with a particular focus on the current upgrades planned to the Morehead State University ground station.

## I. INTRODUCTION

CubeSats are becoming a way to explore space in a more affordable way. An increasing number of organizations between academia, space agencies and companies is investing in developing CubeSats as they can generally be developed with lower budget and in a faster schedule with respect to traditional spacecraft.

As a result of this increase development in the CubeSat/SmallSat market, a new trend emerged: interplanetary CubeSat. Interplanetary CubeSat take advantage of the CubeSat paradigm and of the availability of commercial components developed for Low Earth Orbit (LEO) missions, although they aim to explore deep space. Hence, they are essentially very different from their LEO counterpart.

In particular, interplanetary CubeSats require changes in almost every subsystem. To start, they generally need a propulsion system. In addition, they often need power systems with lower power modes and higher energy storage capabilities since they have more power requirements than LEO missions, due to the presence of propulsion and due to demanding telecommunication systems. Interplanetary CubeSats also require radiation tolerant components as they are significantly far from the protection of the Earth magnetosphere which is instead granted to the LEO CubeSat missions. For what concerns Attitude Determination and Control Subsystem (ADCS), interplanetary CubeSats need a combination of traditional control system and propulsion to avoid the issues of wheel`s saturation outside the Earth`s geomagnetic field. In terms of autonomy, interplanetary missions will have less frequent contact with the ground than LEO missions and they will need agile algorithms to facilitate autonomous on board operations. Finally, one of the most important changes between LEO missions and interplanetary missions is represented by the telecommunication systems. Telecommunication systems for interplanetary CubeSats face harsher environments, longer path distances and have more navigation needs than the LEO CubeSats. For this reason, the design of telecommunication systems for interplanetary missions is extremely challenging and significant development is currently ongoing in the areas of radio design, antenna design and in the design of ground support architectures.

This paper is focused on two future interplanetary CubeSats that will both be launched on board SLS EM-1: Lunar IceCube [9] and LunaH-Map [10]. Lunar IceCube is a 6U CubeSat mission to search for water in solid (ice), liquid, and vapor forms and other lunar volatiles from a low-perigee highly inclined lunar orbit. LunaH-Map is a 6U CubeSat mission designed to search for hydrogen on the permanently shadowed lunar craters. Both missions provide complementary measurements that are extremely important for future lunar exploration human missions.

Given the commonalities between these two missions, as well as other CubeSat missions planned to be launched also on SLS EM-1 (Lunar Flashlight [3], NeaScout [3], BioSentinel, and CuSP), an effort is underway at JPL to develop a common set of telecommunication hardware systems to fit the envelope of these missions' goals. As a result, the two missions (Lunar IceCube and LunaH-Map) share the same radio (Iris transponder), the same low noise amplifiers, the same low gain patch antennas, and they are equipped with very similar Solid State Power Amplifiers (SSPA's) that differ only in the power levels that they provide. Additionally, Lunar IceCube and LunaH-Map will share the use of the Deep Space Network (DSN) antennas and of the Morehead State University 21 m station, which is currently being upgraded especially for this purpose.

The paper is organized as follows: Section II provides a description of the Lunar IceCube spacecraft and telecommunication system; Section III provides a description of the LunaH-Map spacecraft and telecommunication system; Section IV is dedicated to the 21 m antenna at Morehead State University; Section V describes commonalities among the two missions in their end to end telecommunication system; and Section VI is dedicated to the conclusions.

## II. LUNAR ICECUBE

### II.I Mission Overview

Lunar IceCube [7] [8] is a 6U CubeSat designed to prospect for water in solid (ice), liquid, and vapor forms and other lunar volatiles from a low-perigee, highly inclined lunar orbit. The Lunar IceCube mission was been selected through NASA's NextSTEP program for a flight opportunity on Exploration Mission -1 (EM-1). The mission is a partnership between Morehead State University, NASA Goddard Space Flight Center (GSFC), JPL, and the Busek Company. Lunar IceCube will be deployed during lunar trajectory by the Space Launch System (SLS) and use an innovative RF Ion engine to achieve lunar capture and the science orbit (inertially locked, highly elliptical, 100 km periapsis) to investigate the distribution of water (water ice, water vapor, water components) and other volatiles, as a function of time of day, latitude, and regolith composition in the context of mineralogy. Lunar IceCube will include a version of the Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES) [1], developed for CubeSats by GSFC- a compact version of the successful volatile-seeking OSIRIS Rex OVIRS and New Horizons Ralph instruments. The mission will address NASA Strategic Knowledge Gaps related to lunar volatile distribution, and will complement the scientific work of Lunar Flashlight and LunaH-Map 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 PSRs. IceCube will include radiation-hardened subsystems, the JPL Iris radio, a high power solar array and an innovative electric propulsion system. The RF Ion engine (Busek BIT-3 Iodine engine) generates significant delta-v (> 2kms-1) and is one of the enabling technology that will make this and other interplanetary CubeSat science missions feasible. Experts at GSFC will contribute trajectory modelling, navigation and tracking and attitude control modelling and operations. JPL is providing the communications systems engineering and Morehead State University and the NASA DSN will provide ground support for the mission.

Although previous missions (e.g. Clementine, Chandrayaan-1, and LRO/LCROSS) discovered various signatures of OH/H2O, they were not optimized for volatile characterization. BIRCHES is designed with the high spectral resolution (5 nm) and wavelength range (1 to 4 μm) needed to fully characterize water and other volatiles, and distinguish forms of water, including ice. Because the emphasis was on maximizing coverage during the nominal mission, even LRO was not designed to provide repeated systematic (by time of day) measurements of representative features at higher and lower latitudes. IceCube is designed to provide such systematic measurements. The primary science objectives of the Lunar IceCube mission are to enable spectral determination of the composition and distribution of volatiles in the lunar regolith as a function of time of day, latitude, regolith age and composition and to provide a geological context for those measurements through spectral determination of mineral components. Lunar IceCube could determine the relationship between adsorbed and bound water, hydroxyl, and ice throughout the diurnal cycle, and lend insight into understanding the role of external sources, internal sources, and solar wind proton and micrometeorite bombardment in formation, trapping, releasing of water and exosphere formation.

Science data-taking with the BIRCHES payload will occur in two phases, following an approximately 9-month journey on a low energy trajectory initiated at EM1 deployment. Phase 1 will occur between lunar capture and the science orbit, Phase 2 will occur during the science orbit (100 km x 5000 km, equatorial periapsis, nearly polar), highly elliptical, with a repeating coverage pattern that provides overlapping coverage at different lunations. During phase 1, translational propulsion burns are occurring during major portions of most orbits in order to progressively lower periapsis and achieve the desirable incidence angle. Periodically (up to once a week), an orbit will be used for instrument calibration and capture of spectral signatures for larger portions of the lunar disk, traversing from terminator to terminator. Once the nominal full science orbit is achieved, phase 2 will begin, and the main propulsion system will no longer be required. Phase 2, the 'science mission' will last approximately 6 months, 6 lunar cycles, allowing for sufficient collection of systematic measurements as a function of time of day to allow derivation of volatile cycle models.

Development of the Lunar IceCube deep space CubeSat bus leveraged Morehead State University's previous CubeSat mission experience with LEO CubeSat technologies, and incorporates new COTS technologies to develop an evolved, radiation-tolerant 6U CubeSat that can support interplanetary investigator science. The Lunar IceCube bus incorporates high power generation (120 W of continuous power in cislunar space adapted by Pumpkin Inc. from their lower power Supernova design), a radiation-hardened flight computer (Proton 400K made by Space Micro, Inc.), a highly-capable micronized GNC (Guidance, Navigation and Control) system and BCT's (Blue Canyon Technologies) XACT attitude determination and control subsystem. Several options were considered for communications including COTS systems and a high throughput X-band communication system designed by JPL for lunar CubeSat missions. The JPL X-band radio, known as Iris, was selected. Iris 2.1 is a full transponder that is capable of high data throughput and has Doppler ranging capabilities. The primary performance parameters of the Lunar IceCube spacecraft are shown in Table 1.

**Table 1:** Performance parameters of the Lunar IceCube Spacecraft

| | |
|---|---|
| Launch mass (wet mass) | ~14 kg |
| Propellant mass | 1.5 kg |
| Payload mass capability, volume | 3.5 kg, 2.0 U |
| ADCS Pointing accuracy | ±.14 arcseconds (1σ) |
| Orbit knowledge | 10 m, 0.15 m/s |
| Maneuver rate | 3º/s |
| Payload power capability | 17.8 W |
| Prime power generated | 120 W continuous |
| Performance of BIT-3 RF Ion Propulsion System | Nominal thrust: 1.0 mN<br>Nominal Isp (including neutralizer): 2130 s<br>Maximum ΔV capability: 2.9 km/s (at max power)<br>Total impulse capability: 38,800 Ns |

The 6U Lunar IceCube bus owes its heritage to Morehead State's successful 2U CXBN (Cosmic X-ray Background NanoSatellite) mission and 1U KySat-2 missions. Additionally, several of the subsystems have successfully flown on numerous NanoSat and MicroSat missions and most of the COTS subsystems have flight heritage. The combination of flight qualified hardware and innovative solutions to difficult engineering challenges provides for a robust spacecraft bus solution for the Lunar IceCube program. The Lunar IceCube systems are illustrated in Figure 1, and described below.

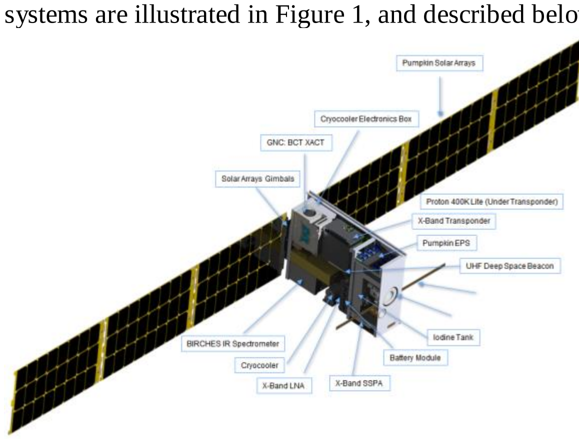


**Figure 1:** Lunar IceCube Bus Systems

**Payload Instrument- BIRCHES**: The Broadband InfraRed Compact, High-resolution Spectrometer, is a compact (1.5U, 2.5 kg, 10-15 W including cryocooler) point spectrometer with a compact cryocooled HgCdTe focal plane array for broadband (1 to 4 µm) measurements, achieving sufficient SNR (>400) and spectral resolution (10 nm) through the use of a Linear Variable Filter to characterize and distinguish important volatiles (water, $H_2S$, $NH_3$, $CO_2$, $CH_4$, OH, organics) and mineral bands. BIRCHES is a miniaturized version of the OVIRS instrument on OSIRIS-Rex. The instrument has built-in flexibility, using an adjustable 4-sided iris, to maintain the same spot size regardless of variations in altitude (by up to a factor of 5) or to vary spot size at a given altitude, as the application requires. Compact instrument electronics are also being developed which can be easily reconfigured to support the instrument in 'imager' mode, once the communication downlink bandwidth becomes available, and the H1RG family of focal plane arrays.

Thermal design is critical for the instrument. The compact and efficient Ricor cryocooler is designed to maintain the detector temperature below 120 K. In order to maintain the optical system below 220 K, a special radiator is dedicated to optics alone, in addition to a smaller radiator to maintain a nominal environment for spacecraft electronics.

For BIRCHES, the NASA Goddard Space Flight Center team developed compact instrument electronics which can be easily reconfigured to support future instruments with H1RG focal plane arrays in 'imager' mode, when the communication downlink bandwidth becomes available. The instrument will enable the lunar ice cube science goals: determination of composition and distribution of volatiles in lunar regolith as a function of time of day, latitude, regolith age and composition, and thus enable understanding of current dynamics of lunar volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles.

**ADCS (Attitude Determination and Control Subsystem):** Attitude control will be provided by the BCT (Blue Canyon Technology) XACT which is an integrated ADCS. This fully integrated system includes star trackers, IMU, and RWAs flight heritage on the MinXSS mission, and can interface with thrusters. Several of the NASA EM-1 CubeSats utilize the BCT XACT.

**Propulsion:** The Busek Company of Natick, MA, with sponsorship from NASA, developed a low-thrust electric propulsion system named BIT-3 (Busek Ion Thruster-3 cm grid). The BIT-3 system [6] is capable of delivering variable Isp and thrust of 2,130 s and 1.0 mN, respectively, at the designed power of 75 W. The BIT-3 RF ion thruster is regarded as the world's first gridded ion thruster ever to operate on iodine propellant.

**C&DH (Command and Data Handling):** The C&DH selected for Lunar IceCube is the Space Micro Inc. Proton P400K-SGMII-2-PCI104S-SD Space Computer. The Proton400K TM computing platform is a high performance, low power radiation hardened processing solution that meets the challenge of the space environments. This product utilizes the Freescale advanced 45 nm dual-core microprocessor and combined with Space Micro's patent pending radiation mitigation technologies.

**Telecommunication System:** Communications with the Lunar IceCube are provided by the JPL X-band Iris transponder, corresponding amplifiers on both receiving and transmitting paths, and dual patch antennas. MSU has a 21 m dish antenna that is becoming part of the DSN. Anticipated downlink data rate is ~128 kbps with the 34 m DSN antennas, and 64 kbps with the MSU 21 m Ground Station. The telecommunications system is described in more detail below.

II.II Telecommunication System & Link Analysis

The telecommunication system for Lunar IceCube is partially inherited from previous planned interplanetary CubeSat missions such as INSPIRE [3] and MarCO [4]. In addition, it shares many commonalities with the other EM-1 CubeSat missions, and in particular with the LunaH-Map telecommunication system described Section III. A block diagram for the Lunar IceCube telecommunication system is shown in Figure 2.

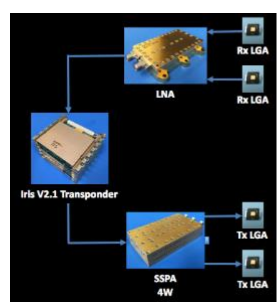


**Figure 2:** Lunar IceCube telecommunication system block diagram

The most significant element of the Lunar IceCube telecommunication system is the Iris radio [15]. Iris V2.1 will be used for Lunar IceCube, as well as other CubeSat missions on-board EM-1 e.g. LunaH-Map, Lunar Flashlight, BioSentinel, NEAScout, and CuSP. A list of key specifications of the Iris V2.1 radio is shown in Table 2.

**Table 2:** Iris V2.1 Specifications

| Specification | Value |
|---|---|
| Downlink Frequencies | 8400 – 8500 MHz |
| Uplink Frequencies | 7145 – 7234 MHz |
| Turn-around Ratio | 880/749 |
| Downlink Symbol Rates | 62.5 bps – 6.25 Msps |
| Uplink Data Rates | 62.5 bps – 8 kbps |
| Modulation Waveforms | PCM/PSK/PM w/ subcarrier, PCM/PM w/ biphase-L, BPSK |
| Telemetry Encoding | Convolutional (r=1/2, k=7), RS (225,223) I=1 or 5, Turbo (1/2, 1/3, 1/6), Concatenated codes |
| Receiver Noise Figure | < 3.5 dB |
| Carrier Tracking Threshold | -151 dBm @ 20 Hz LBW |
| RF Output Power | > 3.8 W |
| Navigation | Sequential/Pseudo-noise Ranging, Delta-DOR |
| Transmit Phase Noise (one-way non-coherent) | -110 dBc/Hz; $\Delta f$ = 100 Hz<br>-117 dBc/Hz; $\Delta f$ = 1 kHz<br>-126 dBc/Hz; $\Delta f$ = 10 kHz<br>-127 dBc/Hz; $\Delta f$ = 100 kHz |
| Oscillator Stability | 0.001 ppm at $\Delta t$ = 1 sec |
| Mass | < 1kg (X/X only) |
| Volume | 0.56 U (excl. SSPA/LNA) |
| Power Consumption | 12.0 W Rx-only<br>33.7 full Tx/Rx |
| Cmd/Tlm Interface | 1 MHz SPI |
| Power Interface | 9-28 Vdc |
| AFT | -20°C to +50°C |
| Dynamics | 14.1 grms random vibration |
| Radiation | > 23.0 krad(Si); 37 MeV-cm$^2$/mg |

The Lunar IceCube mission will use a variety of uplink or downlink data rates depending on the mission phase (cruise vs. science phase) and on the ground station (DSN 34m or MSU 21m) antenna. For uplink or commanding, the Lunar IceCube will use the 62.5 bps data rate for safe mode and 1 kbps for nominal operations. And for downlink, the data rates will range from 62.5 bps for safe mode to 128 kbps (to the 34m antenna) and 64 kbps (to the 21m antenna) for science.

On the receiving path, the Iris radio is connected to the low noise amplifier and two Rx low gain patch antennas, which are placed on opposite side of the spacecraft. And on the transmitting path, a 4W Solid State Power Amplifier (SSPA) is connected to the two Tx low gain patch antennas, which are also placed on the opposite side of the spacecraft.

The 34 m Beam Wave Guide (BWG) antennas at the Goldstone Deep Space Communications Complex, Madrid and Canberra will be utilized to track the Lunar IceCube spacecraft and in addition, the 21 m dish at the Morehead State University (MSU) in Kentucky, US will also be used.

The Lunar IceCube link budgets have been performed with parameters in Figure 3 used as assumptions in the analysis. Maximum distance is assumed to be 1,143,345 km and lunar distance is approximately 400,000 km for this trajectory.

| | | To 34m | To 21m |
|---|---|---|---|
| **S/C PARAMETERS** | | | |
| Rx Noise Figure | dB | 4 | 4 |
| Rx/Tx Circuit Loss | dB | 1 | 1 |
| SC Rx Gain at +/- 90° off boresight | dBi | ≥ 10 | ≥ 10 |
| SC Tx Gain at +/- 45° off boresight | dBi | 4 | 4 |
| **GROUND PARAMETERS** | | | |
| System Noise Temp (SNT) | K | ~27 | ~50 |
| Antenna Pointing Loss | dB | 0.1 | 0.5 |
| Eb/No Required (Turbo 1/6) | dB | -0.1 | -0.1 |

**Figure 3:** Lunar IceCube Link Analysis - Assumptions

Figure 4 shows a summary of the Lunar IceCube link budgets and in all cases, all links can be closed with margin.

| | To 34m | | To 21m | |
|---|---|---|---|---|
| **Mode** | **DL Data Rate** | **Margin** | **DL Data Rate** | **Margin** |
| **Nominal** | 128 kbps, max range | **6.6 dB** | 32 kbps, max range | **3.3 dB** |
| | | | 64 kbps, lunar range | **6.4 dB** |
| **Safe Mode** | 62.5 bps, max range | **38.5 dB** | 62.5 bps, max range | **29.2 dB** |

**Figure 4:** Lunar IceCube Link Analysis - Summary

 

Figure 5 shows the link analysis overview at the maximum distance when all commanding, telemetry, and ranging are enabled.

| | | To 34m | To 21m |
|---|---|---|---|
| | | (max range) | (max range) |
| **TRANSMITTER PARAMETERS** | **Unit** | | |
| SC Tx Power | dBm | 36.02 | 36.02 |
| SC Xmit Circuit Loss | dB | -1 | -1 |
| SC Antenna Gain | dBi | 6.7 | 6.7 |
| DOFF Loss | dB | 0 | 0 |
| Other SC Gain/Loss | dB | -3 | -4 |
| EIRP | dBm | 38.72 | 37.72 |
| **PATH PARAMETERS** | | | |
| Space Loss | dB | -232.19 | -232.19 |
| Atmospheric Attenuation | dB | -0.05 | -0.08 |
| **RECEIVER PARAMETERS** | | | |
| DSN Antenna Gain | dBi | 68.32 | 62.88 |
| DSN Antenna Pnt Loss | dB | -0.1 | -0.5 |
| Polarization Lods | dB | -0.12 | -0.18 |
| **TOTAL POWER SUMMARY** | | | |
| Total Rx Power | dBm | -125.46 | -132.39 |
| SNT due to Antenna MW | K | 21.28 | 40.02 |
| SNT due to Atmosphere | K | 3.37 | 4.92 |
| SNT due to Cosmic Backgnd | K | 2.69 | 2.68 |
| SNT due to the Sun | K | 0 | 0 |
| SNT due to other Hot Bodies | K | 0 | 0 |
| SNT | K | 27.35 | 47.61 |
| Noise Spectra Density | dBm/Hz | -184.23 | -181.82 |
| Received Pt/No | dB-Hz | 58.72 | 49.4 |
| Received Pt/No, mean-2 sigma | dB-Hz | 58.44 | 49.17 |
| Required Pt/No | dB-Hz | 52.16 | 46.14 |
| Pt/No Margin | dB | 6.56 | 3.27 |
| Pt/No Margin, mean-2 sigma | dB | 6.27 | 3.03 |
| **CARRIER PERFORMANCE** | | | |
| Recovered Pt/No | dB-Hz | 58.72 | 49.4 |
| Tlm Carrier Suppression | dB | -35.16 | -35.16 |
| Ranging Carrier Suppression | dB | -0.81 | -0.81 |
| DOR Carrier Suppression | dB | 0 | 0 |
| Carrier Power (ABC) | dBm | -148.85 | -155.77 |
| Received Pc/No | dB-Hz | 35.34 | 26.03 |
| Carrier Loop Noise BW | dB-Hz | 10 | 10 |
| Carrier Phase Error Var | rad^2 | 0 | 0 |
| Carrier Loop SNR (CNR) | dB | 33.69 | 31.71 |
| Recommended CNR | dB | 12 | 12 |
| Carrier Loop SNR Margin | dB | 21.69 | 19.71 |
| **TELEMETRY PERFORMANCE** | | | |
| Tlm Data Suppression | dB | 0 | 0 |
| Ranging Data Suppression | dB | -0.81 | -0.81 |
| DOR Data Suppression | dB | 0 | 0 |
| Received Pd/No | dB-Hz | 57.83 | 48.52 |
| Received Pd/No, mean-2 sigma | dB-Hz | 57.51 | 48.24 |
| Data Rate | dB-Hz | 51.07 | 45.05 |
| Available Eb/No | dB | 6.76 | 3.47 |
| Subcarrier Demod Loss | dB | 0 | 0 |
| Symbol Sync Loss | dB | 0 | 0 |
| Radio Loss | dB | 0.3 | 0.3 |
| Output Eb/No | dB | 6.47 | 3.17 |
| Required Eb/No | dB | -0.1 | -0.1 |
| **Eb/No Margin** | **dB** | **6.56** | **3.27** |

**Figure 5**: Link Analysis Overview for Lunar IceCube Mission

Figure 6 represents a pictorial view of the Lunar IceCube link analysis to the DSN 34 m antenna and Figure 7 shows the pictorial view to the 21 m dish at the MSU; the top half is a picture of the downlink distance and the bottom half is the Eb/No margin at the ground receiver. It is shown here that all links can be closed with margin ≤ 3 dB.

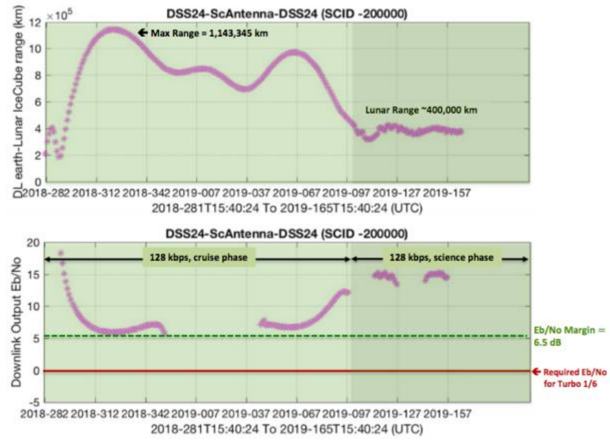


**Figure 6:** Lunar IceCube Link Analysis - Downlink to 34m

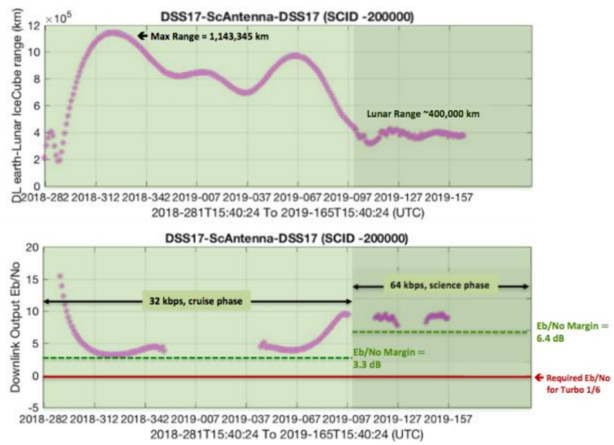


**Figure 7:** Lunar IceCube Link Analysis - Downlink to 21m

## III. LUNAH-MAP

### III.I Mission Overview

The Lunar Polar Hydrogen Mapper (LunaH-Map) is a 6U+ CubeSat funded through NASA Science Mission Directorate's SIMPLEx (Small, Innovative Missions for Planetary Exploration) program. LunaH-Map will make maps of hydrogen enrichments at the Moon's south pole at spatial scales smaller than the extent of the neutron suppressed regions detected by Lunar Prospector [11] and Lunar Reconnaissance Orbiter [12]. Both of these missions used neutron spectrometers to create global maps of hydrogen abundance.

Planetary nuclear spectroscopy relies on detection of leakage neutrons generated by galactic cosmic rays interacting within the top meter of the body's surface. Fast neutrons produced by the GCR interaction undergo further interactions with the regolith. With a mass roughly equivalent to one neutron, hydrogen is particularly efficient at reducing the energy of neutrons. As such, regions with increased hydrogen abundance will have a depressed flux of epithermal (E>0.3 eV) neutrons whereas the flux of thermal (E<0.3 eV) neutrons will be enhanced.

The field of view of an un-collimated neutron detector (like the instrument flown on Lunar Prospector) can be approximated as one and a half times the altitude [13]. As such, LunaH-Map must achieve polar orbit with a periselene below 15 km over the south pole in order to make the required measurements. The Miniature Neutron Spectrometer (Mini-NS), developed by Radiation Monitoring Devices and Arizona State University, is LunaH-Map's only payload. Mini-NS uses CLYC scintillator crystals shielded with gadolinium to detect epithermal neutrons (E>0.3 eV).

LunaH-Map will launch on the first flight of NASA's Space Launch System, Exploration Mission 1. Approximately seven hours after launch, outside the Van Allen Belts, LunaH-Map will be deployed from the Interim Cryogenic Propulsion Stage (ICPS) on an escape trajectory to heliocentric orbit. In order to have sufficient $\Delta V$ to complete a lunar transfer, LunaH-Map uses the new BIT-3 ion propulsion system (IPS) manufactured by Busek. The BIT-3 uses solid iodine propellant to produce up to 1.15 mN thrust with a specific impulse of over 2,000 seconds. A two-axis gimbal allows thrust vectoring for momentum management. The power requirements of the ion propulsion system dictate the size of LunaH-Map's solar arrays. A single-axis gimballed MMA eHawk+ solar array will provide 90W BOL. The IPS will nominally be operated at 65W total system power precluding telemetry downlink, two-way ranging, and science data acquisition during thrust arcs. This constraint drives the design of the transition and science phases of the LunaH-Map mission.

After deployment, LunaH-Map's first maneuver will raise the altitude of the first lunar fly-by to ensure the spacecraft remains captured in the Earth-Moon system. After the fly-by, the spacecraft spends 70 days completing a weak stability boundary transfer to ballistic lunar capture. Once captured into lunar orbit, LunaH-Map enters a ~470-day spiral transition phase to the final 15x3150 km polar, elliptical science orbit. The science orbit is "quasi-frozen" meaning no deterministic orbit maintenance maneuvers are required. Regular statistical maneuvers to correct for perturbations will be planned. The nominal mission plan calls for two months in the science orbit including at least 141 science passes over the south pole. After the conclusion of the science phase, LunaH-Map will perform a final aposelene maneuver to target a disposal impact on the lunar far-side. Full details of the baseline LunaH-Map mission design are presented by Genova and Dunham [14].

During the science phase, LunaH-Map will collect science data over a 30-minute period near periselene. Each science acquisition will include background, unenriched lunar regolith (<85° S) before passing over the south polar, enriched target region (poleward of 85° S). Orbits will be set aside for ranging, telemetry/science data downlink, and command uplink approximately once per day. An additional orbit will be set aside once every 3-5 days for a statistical apogee manuever to correct for unmodeled orbit perturbations.

The LunaH-Map mission is led and managed by Arizona State University. The spacecraft and Mini-NS instrument will be operated from ASU. KinetX and NASA Ames are responsible for mission design and navigation. NASA JPL is providing the Iris deep space transponder and designing the telecommunications system. Blue Canyon Technologies is providing the bus subsystems (EPS, C&DH, ADCS) and flight software. AZ Space Technologies provides engineering and integration leadership for the project.

Key parameters of the LunaH-Map spacecraft are provided in Table 3.

**Table 3:** Key Parameters of the LunaH-Map Spacecraft

| | |
|---|---|
| Launch mass (wet mass) | 14 kg |
| Propellant mass | 1.5 kg |
| Payload mass capability, volume | 3.3 kg, ~2.0 U |
| ADCS maximum achievable pointing accuracy | ±.14 arcseconds (1σ) |
| Payload power | 10W (STBY), 22W (MAX) |
| Bus power generated | 90W BOL |
| Performance of BIT-3 Ion Propulsion System | Nominal thrust: 1.0 mN<br>Nominal Isp (including neutralizer): 2130 s<br>Maximum $\Delta V$ capability: 2.9 km/s (at max power)<br>Total impulse capability: 38,800 Ns |

Figure 8 shows the LunaH-Map spacecraft with key components identified.

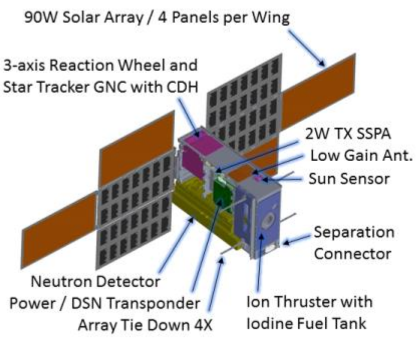


**Figure 8:** LunaH-Map Bus Systems

**Payload Instrument – Mini-NS**

The Mini-NS instrument uses CLYC ($Cs_2LiYCl_6$:Ce) elpasolite scintillator crystals to detect neutrons. Eight 4 cm x 6.3 cm x 2 cm CLYC volumes mated with photomultiplier tubes are arrayed to provide ~200 $cm^2$ of detection area. A shield surrounds the sensor head to absorb thermal neutrons and limit the sensitivity to epithermal neutrons with E > 0.3 eV. A thermoelectrically cooled plate supports the sensor head and will be used to stabilize the crystal temperature during science data acquisition.

FPGA-based digital electronics will readout the eight PMTs and perform pulse shape discrimination to separate detected neutrons from gamma-rays. Both raw and processed data will be stored in the Mini-NS instrument's on-board memory. Only processed neutron count rates will be downlinked due to constraints on data volume.

**Bus Systems – C&DH, EPS, ADCS**

LunaH-Map uses the Blue Canyon Technologies XB1 bus. The XB1 provides C&DH, EPS, and ADCS functionality. BCT is developing the flight software based off heritage from their successful LEO CubeSat programs. The EPS manages power produced by the MMA eHawk+ solar arrays as well as stored energy in six 18650 lithium ion batteries (56W-hr total). The ADCS uses the BCT nano-star tracker in addition to two coarse sun sensors for attitude knowledge. Three 50 mN-m reaction wheels provide attitude control while relying on the BIT-3 for momentum management.

**Propulsion**

Like Lunar IceCube, LunaH-Map uses the Busek BIT-3 propulsion system. The BIT-3 produces up to 1.15 mN of thrust at over 2000 seconds specific impulse. A two-axis ten-degree gimbal allows the BIT-3 to be used for reaction wheel unloading.

III.II Telecommunication System and Link Analysis

As in Lunar IceCube, the telecommunication system for LunaH-Map is partially inherited from previous planned interplanetary CubeSat missions such as INSPIRE [3] and MarCO [4]. A block diagram for the telecommunication system is shown in Figure 9.

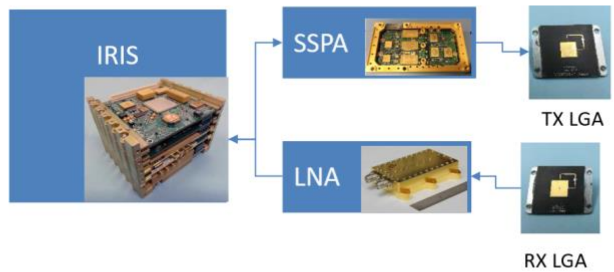


**Figure 9:** LunaH-Map telecommunication system block diagram

The key component of the telecommunication system is the Iris radio [3]. Designed to work at both Near Earth and Deep Space X-Band frequency allocations, the Iris radio provides telecommunication and navigation services to the CubeSat missions. It has an 880/749 turn around ratio and less than 5 dB noise figure. The uplink modulation is PCM/PSK/PM with BCH encoding and a variety of data rates offered. LunaH-Map will use 62.5 bps data rate as its safe mode and 1 Kbps data rate for normal operations. The downlink modulation is BPSK with several encoding options (Manchester, suppressed carrier, subcarrier) and coding schemes (Reed Solomon, Convolutional, Turbo). Downlink data rates options range from 62.5 bps to 256 Kbps. LunaH-Map will use a variety of downlink data rates depending on the particular phase of the mission (cruise vs. science phase) and on the ground station used (34 m dish vs. 21 m dish). Data rates will range from a safe mode of 62.5 bps and a high data rate mode for science data downloading of 128 Kbps.

The Iris radio is connected, on the receiving path, to the low noise amplifier and the two low gain receiving patch antennas which are placed on opposite side of the spacecraft to maximize coverage [10].

The Iris radio is also connected, on the transmitting path, to the Solid State Power Amplifier (SSPA) which provides two watts of power amplification for the signal. The SSPA is then connected to the two low gain transmit antenna also placed on opposite sides of the spacecraft [10].

The ground receivers to be used for the LunaH-Map are the 34 m antennas of DSN located in Goldstone (California), Madrid (Spain), and Canberra (Australia), and the 21 m antenna at Morehead State University. [5]

Link analysis has been computed at the maximum range and at the lunar orbit and shows margin in both situations.

Figure 10 shows results for the link analysis for LunaH-Map mission. Four cases are shown: maximum distance using DSN (34 m dish) stations, lunar distance using DSN (34 m dish) stations, maximum distance using the Morehead State University 21 m dish and lunar distance using the Morehead State University 21 m dish. In all the cases, the link can be closed with margin. A couple of significant notes on this analysis are:

- It can be noticed a very large pointing loss: this is because we are not assuming to point the antenna in any way besides being in its +/- 70 degree cone. This is an operational choice more than a constraint.
- The requirement of Eb/N0 is different for the second case (DSN at lunar distance). This is because in that case the mission will use a very high data rate which requires a lower rate Turbo coding (Turbo ½) due to bandwidth constraints per NTIA regulations. For all the other data rates, the Turbo 1/6 coding is assumed.
- Radio losses at the ground receiver are higher when using the Morehead University Station: this is actually an assumption because the MSU receiver has not been tested. In reality, the expected performance of the receiver is very close to the ones for DSN, so once it is tested, this number will be lowered in the link analysis.

| Item | Symbol | Units | Downlink Maximum Range (DSN) | Downlink Lunar Distance (DSN) | Downlink Maximum Range (Morehead) | Downlink Lunar Distance (Morehead) |
|---|---|---|---|---|---|---|
| **EIRP:** | | | | | | |
| Transmitter Power | P | dBW | 3.00 | 3.00 | 3.00 | 3.00 |
| Line Loss/Waveguide Loss | $L_l$ | dB | -2.63 | -2.63 | -2.63 | -2.63 |
| Transmit Antenna Gain (net) | $G_t$ | dBi | 6.70 | 6.70 | 6.70 | 6.70 |
| Equiv. Isotropic Radiated Power | EIRP | dBW | 7.07 | 7.07 | 7.07 | 7.07 |
| **Receive Antenna Gain:** | | | | | | |
| Frequency | f | Ghz | 8.49 | 8.49 | 8.49 | 8.49 |
| Receive Antenna Diameter | $D_r$ | m | 34.00 | 34.00 | 21.00 | 21.00 |
| Receive Antenna efficiency | η | n/a | 0.75 | 0.75 | 0.55 | 0.55 |
| Receive Antenna Gain | $G_r$ | dBi | 68.37 | 68.37 | 62.84 | 62.84 |
| **Free Space Loss:** | | | | | | |
| Propagation Path Length | S | km | 1,002,990.00 | 400,000.00 | 1,002,990.00 | 400,000.00 |
| Free Space Loss | $L_s$ | dB | -231.05 | -223.07 | -231.05 | -223.07 |
| **Transmission Path and Pointing Losses:** | | | | | | |
| Transmit Antenna Pointing Loss | $L_{pt}$ | dB | -8.00 | -8.00 | -8.00 | -8.00 |
| Receive Antenna Pointing Loss | $L_{pr}$ | dB | -0.10 | -0.10 | -0.50 | -0.50 |
| Receive Antenna Polarization Losses | $L_{pol}$ | dB | -0.14 | -0.14 | -0.18 | -0.18 |
| Atmospheric Losses | $L_{atmo}$ | dB | -0.20 | -0.20 | -0.29 | -0.29 |
| Radio Losses | $L_{radio}$ | dB | -0.50 | -0.50 | -1.50 | -1.50 |
| Total Additional Losses | | dB | -8.94 | -8.94 | -10.47 | -10.47 |
| **Data Rate:** | | | | | | |
| Data Rate | R | sps | 32,000.00 | 128,000.00 | 2,000.00 | 16,000.00 |
| Data Rate | 10 log( R ) | dBbps | 45.05 | 51.07 | 33.01 | 42.04 |
| Data | | | | | | |
| **Boltzman's Constant:** | | | | | | |
| Boltzman's Constant | 10 log(k) | dBW/(Hz* | -228.60 | -228.60 | -228.60 | -228.60 |
| **System Noise Temperature:** | | | | | | |
| Antenna noise | $T_{ant}$ | K | 14.77 | 14.77 | | |
| Atmosphere | $T_{sky}$ | K | 12.62 | 12.62 | | |
| Cosmic | $T_{el}$ | K | 2.61 | 2.61 | | |
| System Noise Temperature | $T_s$ | K | 30.00 | 30.00 | 62.20 | 62.20 |
| System Noise Temperature | $10 \log(T_s)$ | dBK | 14.77 | 14.77 | 17.94 | 17.94 |
| **SNR (Pt/N0)** | | dB - Hz | 49.77 | 57.76 | 40.54 | 48.53 |
| **Modulation** | | | | | | |
| Telemetry data suppression | $L_{tel\_sup}$ | dB | 0.00 | 0.00 | 0.00 | 0.00 |
| Ranging data suppression | $L_{rgn\_sup}$ | dB | -0.83 | -0.83 | -0.83 | -0.83 |
| **$E_b/N_o$** | | dB | 3.39 | 5.36 | 5.20 | 4.16 |
| **$E_b/N_o$ required** | | dB | 0.10 | 1.10 | 0.10 | 0.10 |
| **Margin** | | dB | **3.29** | **4.26** | **5.10** | **4.06** |

**Figure 10:** Link Analysis Overview for LunaH-Map Mission

Another important analysis, is coverage analysis. Coverage looks at the duration of passes, visibility and overall data rate profile versus range. An example of range variation for LunaH-Map orbit is shown in Figure 11 Statistics on expected pass durations are shown in Table 4.

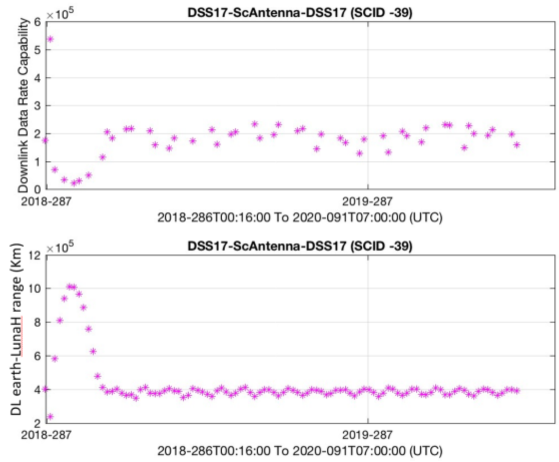


**Figure 11:** Data rate capability for LunaH-Map while using the MSU 21 m dish.

**Table 4:** Coverage intervals duration.

| Contacts | DSN (Goldstone) | DSN (Madrid) | DSN (Canberra) | MSU |
|---|---|---|---|---|
| Min. duration | 7 hours | 6.5 hours | 7 hours | 7.5 hours |
| Average duration | 11 hours | 11 hours | 11 hours | 11.5 hours |
| Max. duration | 14 hours | 14.5 hours | 14 hours | 14 hours |

In Figure 11 the range of the LunaH-Map mission is shown. In addition to the range, the first plot provides a profile of the data rate capabilities when using the Morehead State University 21 m antenna. This plot is intended as an example and it does not assume the relaxed pointing of 70 degrees previously discussed. As a result, the possible data rate capability for LunaH-Map is theoretically higher.

The coverage table (Table 4) shows the minimum, maximum and average duration of contacts between the LunaH-Map spacecraft and all the four possible ground receivers. It is important to notice that this analysis is based on geometry and it does not take in advance any scheduling conflict among the 13 EM-1 CubeSats. To solve these scheduling conflicts and to maximize the time in which each mission is able to communicate to the ground, DSN is studying strategies such as MSPA (Multiple Spacecraft Per Antenna), although it is expected that the total amount of telecommunication time allowed per mission will still be less than the geometric coverage.

One last analysis that was performed for LunaH-Map is the ranging analysis which looks at the precision that can be achieved while using the Iris radio, and the ground receivers to perform ranging measurements at the different points of the trajectory. Results are shown in Table 5.

**Table 5:** 3 sigma ranging error for different ground receiver.

| **3 sigma ranging error (LunaH-Map)** | **DSN (m)** | **MSU (m)** |
|---|---|---|
| Maximum range | 0.73 | 13.04 |
| Lunar distance | 0.24 | 2.21 |

As expected, the larger dishes of DSN (34 m) allow more precision in the radiometric measurements with respect to the 21 m ground station.

## IV. MOREHEAD STATE UNIVERSITY GROUND STATION

In 2016 a project was initiated to upgrade the Morehead State University 21 m antenna system for integration into the DSN as an auxiliary station to support smallsat missions [2]. The project, funded by NASA's Advanced Exploration Systems (AES) is intended to serve as a test case to define a path for integration of other non-NASA ground stations to support the projected increasing number of smallsat missions. The project has focused on upgrading the 21 m to DSN compatibility through the implementation of DSN 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.

The 21-meter class antenna system shown in Figure 12, was developed by Morehead State University in 2006 as a multi-purpose instrument, serving as a university-based ground station as a radio telescope for astronomical research and as an experimental station for communications systems development. The instrument is a unique educational tool that provides an active laboratory for students to have hands-on learning experiences with the intricacies of satellite telecommunications and radio astronomy. The 21 m supports undergraduate research in astrophysics, satellite telecommunications, RF and electrical engineering, and software development. From its inception, it was anticipated that the 21 m would provide telemetry, command and tracking services for small, low power satellites performing research in the lunar vicinity, at Earth-Sun Lagrange points, and at Near Earth Asteroids (NEAs) and potentially out to Mars at low data rates. One of the primary uses of the 21 m system is to provide ground operations services for small satellite missions operated by Morehead State University and its partners. The students and staff of MSU have gained valuable experience in space operations and the 21-m's performance has been vetted through these activities.

**Figure 12:** Morehead State University 21 m Ground Station-DSN DSS-17

The upgrade consisted of developing a simplified, single channel (Deep Space X-band) version of the DSN Block V Receiver and DSN Block VI Exciter for the 21 m. These systems include re-engineered versions of the uplink tracking and command system (UPL), the downlink tracking and telemetry system (DTT), the data capture and delivery system (DCD) and a "lite' version of the network monitor and control (NMC) system. A system of servers and network systems provide a secure link to the NASA IONet to process schedule requests for DSN services, to send spacecraft commands from the spacecraft operators, and to transfer telemetry and tracking data as well as network monitor data. Upgrades also included development of an improved, high power X-band feed with cryogenically cooled low noise amplifiers. A Hydrogen maser frequency standard was added to support tracking and ranging at the precision levels required by the DSN. These upgrades have resulted in significant improvement in the performance, sensitivity and capability of the 21 m station. The 21 m will have the capability to provide all services associated with a DSN station, albeit at a reduced performance level compared with the standard

DSN 34 m Beam Wave Guide (BWG) station. Performance targets for the 21 m, labelled DSS-17 in its DSN role, are listed in Table 6 below.

**Table 6:** DSS-17 performance targets.

| Performance Measure | Post-Upgraded Targets |
|---|---|
| X-Band Frequency Range | 7.0 – 8.5 GHz |
| LNA Temperature | < 20 K |
| System Temperature $T_{sys}$ | <100 K |
| Antenna Gain | 62.7 dBi (@8.4 GHz) |
| System Noise Spectral Density | <-178 dBm/Hz |
| G/T at 5° Elevation | 40.4 dBi/K |
| Time Standard | H-MASER (1ns/day) |
| EIRP | 93.7 dBW |
| HPBW | 0.1150 deg |
| SLE Compliant | Yes |
| CCSDS Capable | Yes |

The DSS-17 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; thereby enabling interplanetary research with small satellites.

## V. COMMONALITIES IN THE END TO END DEVELOPMENT OF THE TELECOMMUNICATION SYSTEM

An effort is underway at JPL to develop a common set of telecom hardware to fit the envelop of several EM-1 missions, by using the Iris V2.1 radio and DSN 34 m plus MSU 21 m ground stations as an end to end system. Figure 13 shows an overview of the end to end telecommunication subsystem for the three lunar missions (Lunar IceCube, LunaH-Map, and Lunar Flashlight) on-board EM-1 with such scenario.

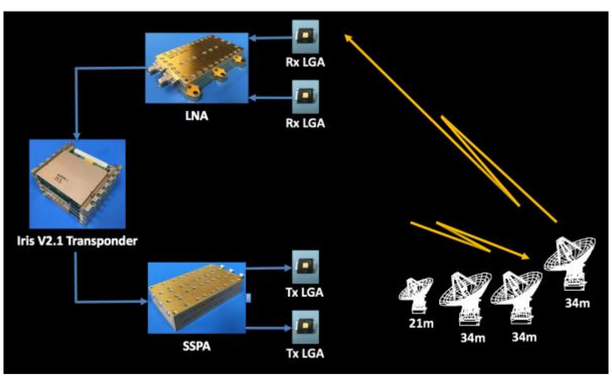


**Figure 13: End to end system overview for three lunar missions on-board EM-1 using Iris (Lunar IceCube, LunaH-Map, Lunar Flashlight)**

Key to all three of the lunar missions here is the Iris V2.1, and on the receiving path is the two low gain antenna (LGA) and LNA, and on the transmitting path is the two low gain antenna (LGA) and the SSPA. All (but LunaH-Map who will be using the 2W SSPA) will be using the 4W SSPA in the transmitting path, and all will be utilizing the DSN 34m and MSU 21 ground stations pending frequency licensing approval.

Figure 14 shows an overview of the end to end telecommunication systems for the other three CubeSats on-board EM-1 that plan to use the Iris V2.1 transponder (BioSentinel, NEAScout, and CuSP) with similar architecture as in Figure 13, except that since these missions are going further away than the moon a spacecraft medium gain antenna (MGA) is utilized. The flight configuration in the transmit chain with the MGA varies slightly for each mission e.g. BioSentinel combines the MGA with an LGA, CuSP carries the risk of flying with only one Tx MGA, and NEAScout plans to fly two additional LGA's to minimize the risk of flying a deployable MGA in the transmit path. Nevertheless, it can be shown that all other telecommunication hardware is the same as those shown in in Figure 13, creating commonalities amongst the six EM-1 CubeSats.

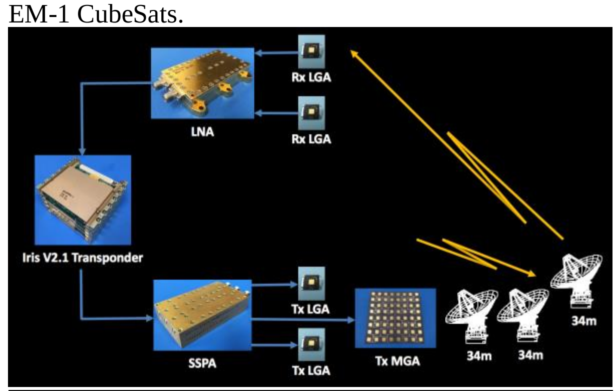


**Figure 14: End to end system overview for three non-lunar missions on-board EM-1 using Iris (BioSentinel, NEAScout, CuSP)**

## VI. CONCLUSION

In this paper, an overview of two missions (Lunar IceCube and LunaH-Map) is presented. For each mission, a brief description of the spacecraft and of the mission objectives is provided. Then, the telecommunication system design is described in greater details. Finally, given that both these two missions will make use of the 21 m antenna at Morehead State University, the facility is described and the work perform to integrate this station into the Deep Space

Network is also presented. Finally, attention is given to the commonalities among these missions which are mostly in the hardware selection and in the ground receiver selection. In terms of differences, the two missions differ mostly in the selection of the SSPA (4W vs. 2W), in the selection of the data rates and in the trajectory/operation concept.

Both missions have successfully passed Critical Design Reviews (CDRs) and the teams are working toward starting integrating and testing the different components.

## VII. ACKNOWLEDGMENTS

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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