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

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Outline

- Introduction
- Lunar IceCube
  - Mission Overview
  - Telecommunication System
- LunaH-Map
  - Mission Overview
  - Telecommunication System
- DSS-17
- Missions` commonalities

Introduction (1/2)

- CubeSat are becoming a way to explore space in a more affordable way: they can generally be developed with lower budget and in a faster schedule than traditional spacecraft.

- Recently, a new trend emerged: interplanetary CubeSat. They take advantage of the CubeSat paradigm and of the commercial components developed for Low Earth Orbit (LEO) missions, although they aim to explore deep space.

- Interplanetary CubeSat require changes with respect to LEO missions:

  - **Propulsion systems**: generally not needed in LEO, but almost a "must" beyond LEO

  - **Power systems**: solar power is greatly reduced for CubeSats that travel farther away from the Sun than the Earth. Also, lower power modes and higher energy storage capabilities are needed to support propulsion and more demanding telecommunication systems.

  - **Radiation**: radiation tolerant components are needed as missions are significantly longer than LEO missions and are also farther away from the Earth magnetosphere.

  - **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.

  - **Autonomy**: interplanetary missions will have less frequent contact with the ground and will need agile algorithms to facilitate autonomous on board operations.

  - **Telecommunication systems**: interplanetary CubeSats face harsher environments, longer path distances and have more navigation needs than the LEO CubeSats.

Introduction (2/2)

- This paper is focused on two future CubeSats that will both be launched on board SLS EM-1:
  - Lunar IceCube: 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: a 6U CubeSat mission designed to search for hydrogen on the permanently shadowed lunar craters.

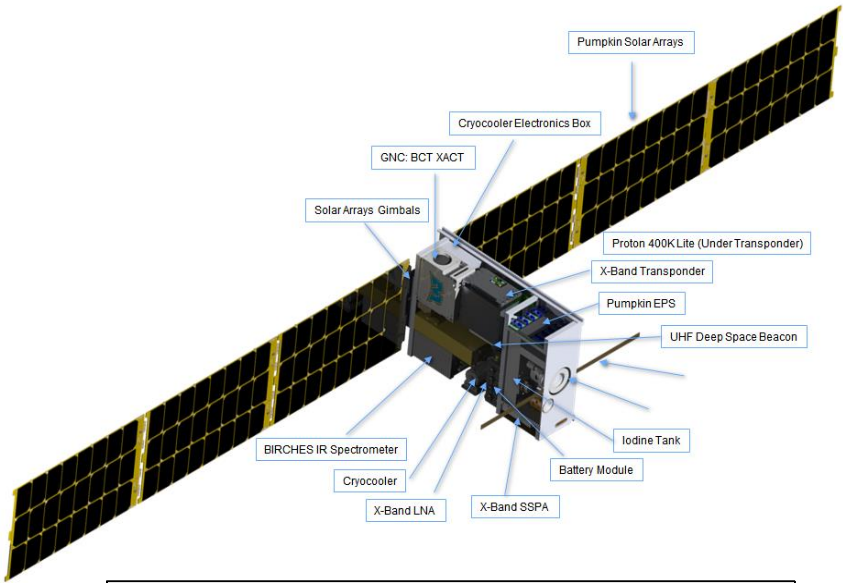
- Given the commonalities between these two missions, as well as other CubeSat missions planned to be launched also on SLS EM-1, an effort is underway at JPL to develop a common set of telecommunication hardware systems to fit the envelope of these missions' goals.

- 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 including the Morehead State University 21 m station that is currently being upgraded for EM-1 mission support and will become a formal ground station element of the NASA Deep Space Network as Deep Space Station-17 (DSS-17)

Lunar IceCube

- Lunar IceCube 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.
- Lunar IceCube will be launched on SLS EM-1, deployed during lunar trajectory, and use an RF Ion engine to achieve lunar capture.
- 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.
- Payload: Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES), a compact version of the successful volatile-seeking OSIRIS Rex OVIRS and New Horizons Ralph instruments. BIRCHES is designed with the spectral resolution and wavelength range needed to fully characterize water and other volatiles (water, H_2S, NH_3, CO_2, CH_4, OH, organics), and to distinguish forms of water, including ice.
- Science data-taking with the BIRCHES payload will occur in two phases, following an approximately 9-month cruise.
  - Phase 1: between lunar capture and the science orbit.
  - Phase 2: 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.
- Partnership between Morehead State University, NASA Goddard Space Flight Center (GSFC), JPL, and the Busek Company.



Lunar IceCube
Spacecraft configuration

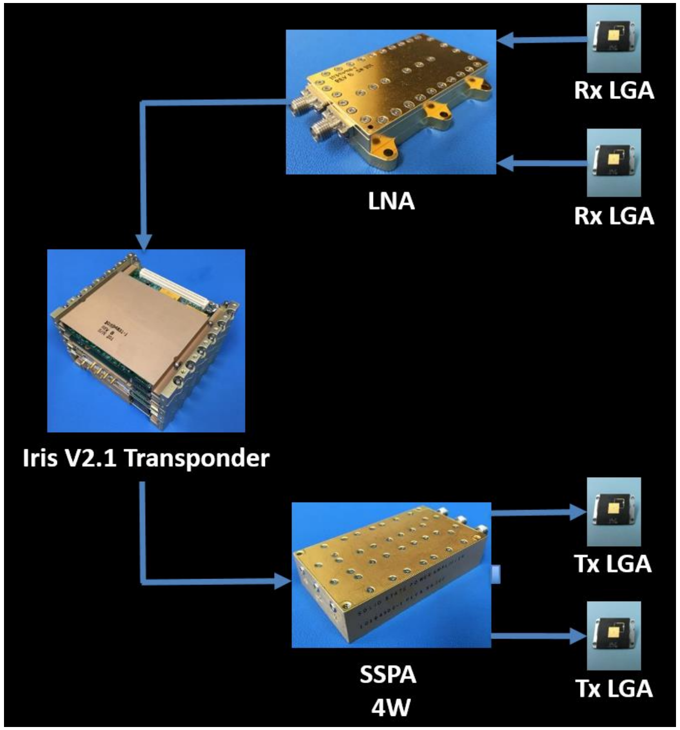
Lunar IceCube: Subsystems

- 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 has built-in flexibility, using an adjustable 4-sided iris, to maintain the same spot size regardless of variations in altitude
  - Thermal design is critical for the instrument as it can seriously affect the ability for the instrument to differentiate among the different volatiles and bands.
    - The 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.
- ADCS (Attitude Determination and Control Subsystem): Attitude control will be provided by the BCT (Blue Canyon Technology) XACT which is an integrated ADCS featuring star trackers, IMU, and RWAs
- Propulsion: BIT-3 (Busek Ion Thruster-3 cm grid)capable of delivering variable Isp and thrust of 2,130 s and 1.0 mN, respectively, at the designed power of 75 W.
- C&DH (Command and Data Handling): Space Micro Inc. Proton P400K-SGMII-2-PCI104S-SD Space Computer (high performance, low power radiation hardened)

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	3°/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 Nominal Isp (including neutralizer): 2130 s Maximum ΔV capability: 2.9 km/s (at max power) Total impulse capability: 38,800 Ns

Lunar IceCube spacecraft parameters

Lunar Ice Cube: Telecommunication

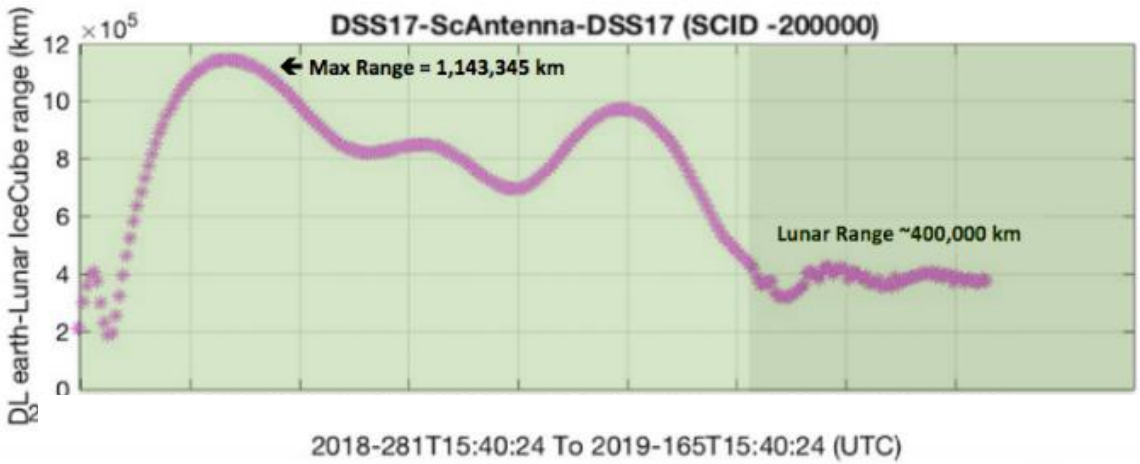


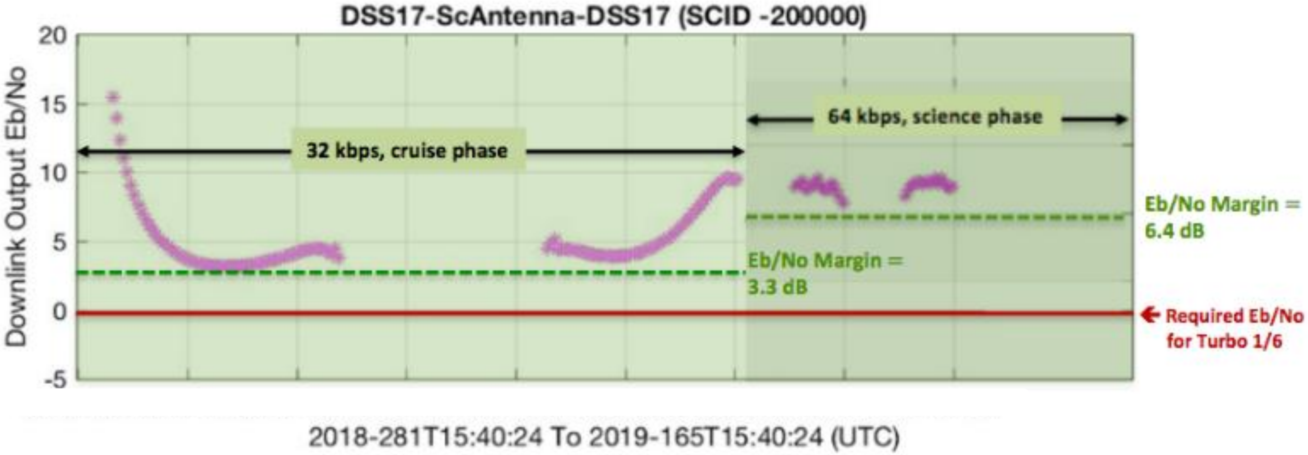
Lunar Ice Cube Telecommunication system block diagram

IRIS 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
Oscillator Stability	0.001 ppm at Δt = 1 sec
Mass	< 1kg (X/X only)
Power Consumption	12.0 W Rx-only 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

Lunar IceCube: Telecom Analysis





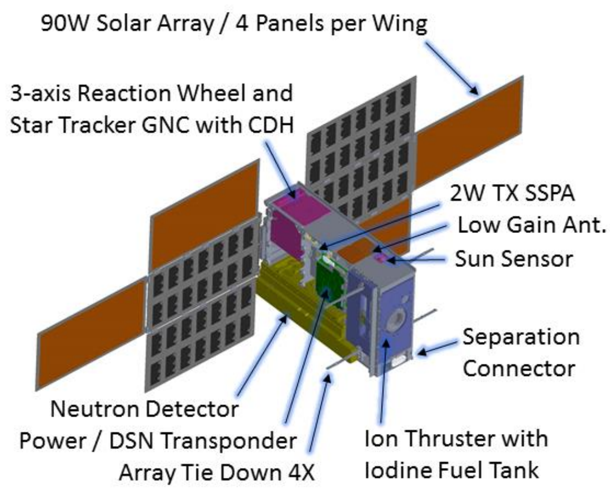
Lunar IceCube Link Analysis – Downlink to 21m

		To 34m (max range)	To 21m (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**

Lunar IceCube link budget

LunaH-Map Mission Plan

- The Lunar Polar Hydrogen Mapper (LunaH-Map) is a 6U+ CubeSat funded through NASA SIMPLEx (Small, Innovative Missions for Planetary Exploration) program.
- LunaH-Map will map hydrogen enrichments at the Moon's south pole at spatial scales smaller than the neutron suppressed regions detected by Lunar Prospector and Lunar Reconnaissance Orbiter.
- LunaH-Map will launch on NASA's Space Launch System, EM-1
- 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 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.
- After the conclusion of the science phase, LunaH-Map will perform a final maneuver to target a disposal impact on the lunar far-side.
- During science phase (2 months), 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).
- The mission is led by Arizona State University. Partners include: Kinetix, NASA Ames, JPL, Blue Canyon Technologies and AZ space technologies.



LunaH-Map spacecraft configuration

LunaH-Map: Subsystems

- 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-digital electronics will readout the eight PMTs and perform pulse shape discrimination to separate detected neutrons from gamma-rays. Raw and processed data will be stored in the instrument's on-board memory. Only processed neutron count rates will be downlinked.

- 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.

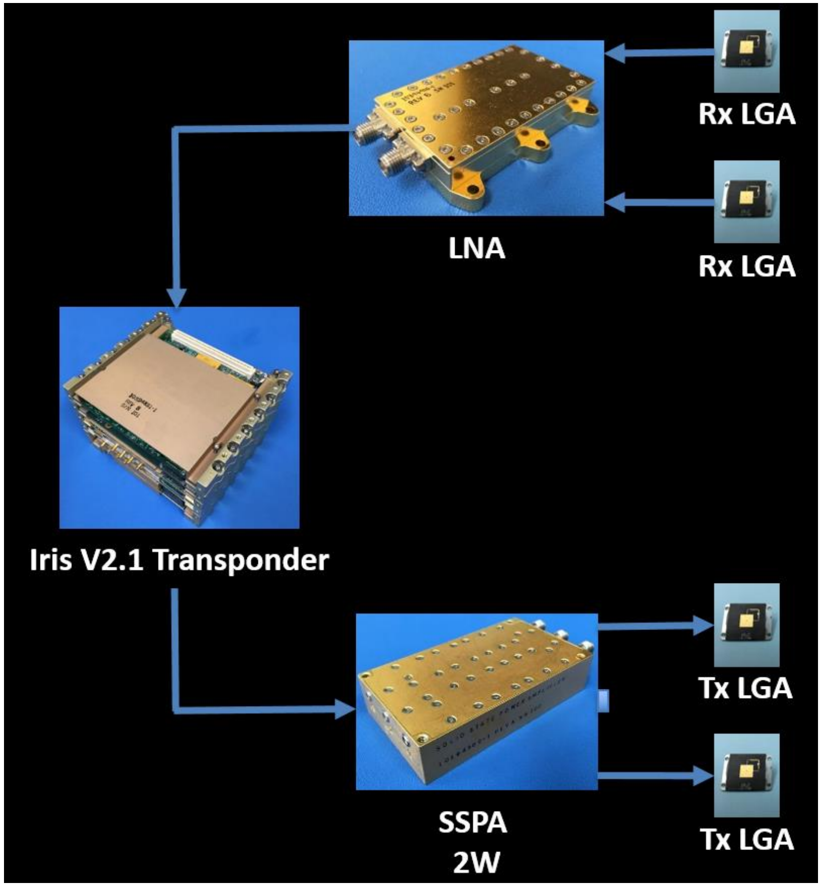
- Propulsion: LunaH-Map uses the Busek BIT-3 propulsion system.

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 Nominal Isp (including neutralizer): 2130 s Maximum ΔV capability: 2.9 km/s (at max power) Total impulse capability: 38,800 Ns

LunaH-Map spacecraft parameters

LunaH-Map: Telecommunications

- The key component is the Iris radio:
  - Functional at Near Earth and Deep Space X-Band frequency
  - 880/749 turn around ratio
  - Less than 5 dB noise figure.
  - Uplink modulation is PCM/PSK/PM with BCH encoding
    - LunaH-Map will use 62.5 bps for safe mode and 1 Kbps for normal operations.
  - Downlink modulation is BPSK with several encoding options (Manchester, suppressed carrier, subcarrier) and coding schemes (Reed Solomon, Convolutional, Turbo).
    - 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.
- Receive path→ Iris radio is connected 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
- Transmit path → Iris radio is connected to the 2W Solid State Power Amplifier (SSPA) and to the two low gain transmit antenna also placed on opposite sides of the spacecraft [10].
- Ground receivers→ 34 m antennas of DSN located in Goldstone (California), Madrid (Spain), and Canberra (Australia), and the 21 m antenna at Morehead State University

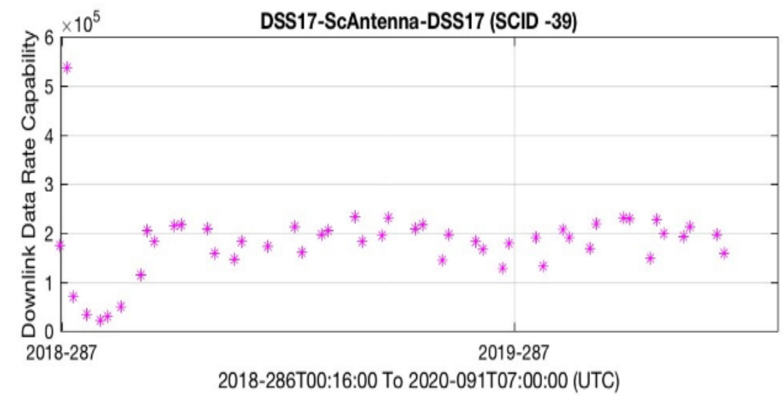


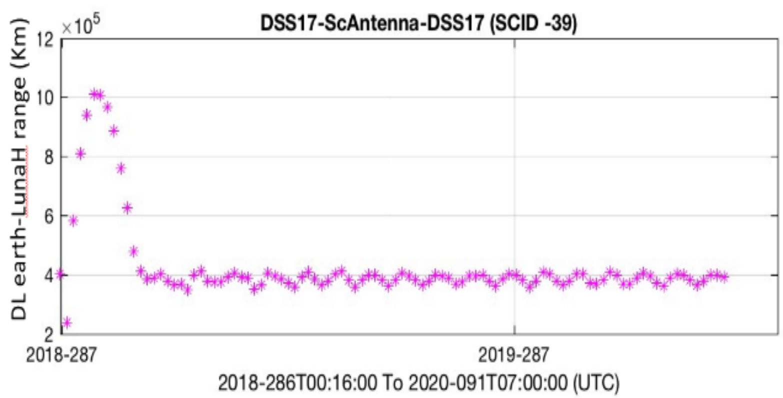
LunaH-Map telecommunication system overview

LunaH-Map: Telecommunication Analysis

Item	Symbol	Units	Downlink Maximum Range (DSN)	Downlink Lunar Distance (DSN)	Downlink Maximum Range (MSU)	Downlink Lunar Distance (MSU)
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
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 Gain	G_r	dBi	68.37	68.37	62.84	62.84
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
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	R	sps	32,000.00	128,000.00	2,000.00	16,000.00
System Noise Temperature	T_s	K	30.00	30.00	62.20	62.20
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**

LunaH-Map link analysis summary





Data rate capability for LunaH-Map while using the MSU 21 m dish

DSS-17

- In 2016 a project was initiated to upgrade the Morehead State University 21 m antenna system for integration into the DSN
- The project is intended as a test case to define a path for integration of 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 capabilities, the implementation of Space-link Extension (SLE) protocol, CCSDS data standardization, and asset scheduling capabilities.
- The 21-meter antenna 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 provides an active laboratory for students to have hands-on learning experiences.
- From its inception, it was anticipated that the 21 m would provide telemetry, command and tracking services for small, low power satellites 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.

Morehead State University 21 m Ground Station-DSN DSS-17

DSS-17: Upgrades and Performance

- The upgrade consisted of a simplified, single channel (Deep Space X-band) version of the DSN Block V Receiver and DSN Block VI Exciter.

- Upgrades 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) → to **achieve compatibility** with respect to the CCSDS protocol standards.
  - Addition of a system of servers and links between MSU and the NASA IONet → to **allow** for **processing schedule** requests for DSN, to **send spacecraft commands** from the spacecraft operators, and to **transfer telemetry** and **tracking data.**
  - Development of a high power X-band feed with cryogenically cooled low noise amplifiers → to **reduce the system noise** temperature of the station
  - Addition of an hydrogen maser frequency standard → to **support tracking and ranging** at the precision required by DSN.

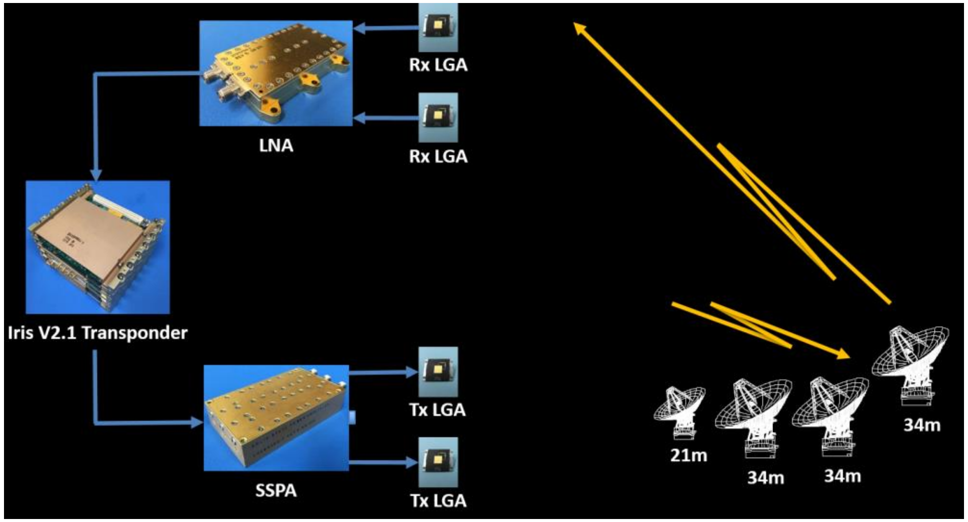
Performance Measure	Post-Upgraded Targets
X-Band Frequency Range	7.0 – 8.5 GHz
LNA Temperature	< 20 K
System Temperature T_{sys}	<100 K
Antenna Gain	62.7 dBi (@8.4 GHz)
System Noise Spectral Density	<-178 dBm/Hz
G/T at 5° Elevation	40.4 dBi/K
Time Standard	H-MASER (1ns/day)
EIRP	93.7 dBW
HPBW	0.1150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

DSS-17 parameters

End to end telecommunication systems commonalities

- JPL is developing a common set of telecom hardware to fit the envelop of several EM-1 missions

- For LunaH-Map and Lunar IceCube commonalities in the end to end telecommunication system are as follows:
    - Same Iris V2.1 radio
    - Same LNA
    - Same tx and rx LGA
    - Similar SSPA (Lunar IceCube will use the 4 W version, while LunaH-Map will use the 2 W version)
    - Use of the DSN 34 m dishes
    - Use of the 21 m MSU ground station (DSS17)



End to end telecommunication system for both lunar missions

Summary

- An overview of two missions (Lunar IceCube and LunaH-Map) is presented.
- For each mission, a description of the spacecraft and of the mission objectives is provided.
- The telecommunication system design is described in greater details.
- The 21 m antenna at Morehead State University is described and the work perform to integrate this station into the Deep Space Network is presented.
- Commonalities among the missions are discussed.
- Both missions have successfully passed Critical Design Reviews (CDRs) and the teams are working toward starting integrating and testing the different components.

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- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Thank you!

Questions?