Telecommunication System Design for Interplanetary CubeSat Missions: LunaH-Map

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***Abstract*—The[1] Lunar Hydrogen Mapper (LunaH-Map) will be one of 13 CubeSats to launch on the first integrated flight of NASA's Space Launch System and Orion spacecraft in 2018. The goal of the LunaH-Map mission is to map the hydrogen content of the entire South Pole of the moon, including permanently shadowed regions at high resolution. The spacecraft is a 6 U CubeSat and the main instrument is a neutron spectrometer which will be used to perform the measurements required to accomplish the primary science objective. Once LunaH-Map reaches the Moon, the spacecraft will perform a 60-day science mission, consisting of 141 science orbits during which the measurements will be taken. In the design of the LunaH-Map spacecraft, one of the main challenges is the telecommunication system as the spacecraft needs the ability to relay data during the long cruise phase and during the science phase. In addition, the telecommunication system needs to support the main navigation functions required to reach the Moon and to insert in the highly elliptical orbit required for the science phase. This paper covers the main aspects of the telecommunication design for the mission including: link and coverage analysis, waveform selection and spectral constraints, hardware selection and ground station coordination.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. TELECOMMUNICATION REQUIREMENTS 2
3. TELECOMMUNICATION ANALYSIS 2
4. TELECOMMUNICATION COMPONENTS 5
5. INTEGRATION AND TEST 6
6. SUMMARY FUTURE WORK 6
ACKNOWLEDGEMENTS 7
REFERENCES 7
BIOGRAPHY 7

1. INTRODUCTION

LunaH-Map spacecraft [1] [2] is a mission designed to map the distribution of hydrogen-abundances within permanently shadowed craters at the Lunar South Pole. In addition, LunaH-Map will determine the hydrogen-layering structure of permanently shadowed craters at the Lunar South Pole. The value of the LunaH-Map mission is tied to the unprecedented high spatial resolution that will be achieved for neutron counting data at the Moon. LunaH-Map will, in fact, acquire the highest spatial resolution neutron data ever acquired from an orbital spacecraft platform anywhere in the Solar Systems. The resulting hydrogen maps will respond to a variety of NASA science goal and push the boundaries of the capabilities of small spacecraft.

LunaH-Map is designed as a 6 unit CubeSat that will orbit the lunar South Pole at low altitude and produce high spatial resolution maps of the lateral and vertical distribution of hydrogen in the lunar regolith. LunaH-Map will use a new neutron detector material that can easily be accommodated within a CubeSat due to its small size. This instrument, designed and produced by RMD, will function similarly to the detector on lunar prospector (LPNS) but a significantly higher resolution.

The mission architecture, designed by KinetiX and NASA Ames, allows for 60-day science missions in a highly elliptical orbit with perilune centered on Shackleton Crater at 5 km altitude. There is sufficient fuel to allow for 141 science orbit which will cover craters identified as high priority science targets.

The spacecraft components selection was based on what is currently available for CubeSats plus some developments for any needed capabilities. Components currently selected for

[1] Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

978-1-5090-1613-6/17//$31.00 ©2017 IEEE

LunaH-Map spacecraft include: the deployable solar panel by MMA, the XACT attitude and control determination by BCT, and the IRIS radio by JPL. In particular, JPL is contributing to the LunaH-Map mission by providing the telecommunication subsystem (IRIS radio, LNA, SSPA and low gain antennas) and by providing DSN ground services.

The paper is organized as follows: Section 2 outlines the telecommunication requirements for LunaH-Map mission. Section 3 presents the telecommunication analysis. The components selected are described in Section 4. Section 5 is dedicated to integration and test. Section 6 provides a summary and details on future work.

2. TELECOMMUNICATION REQUIREMENTS

The telecommunication subsystem for LunaH-Map needs to be designed as to be able to support both telecommunication and navigation functionality for all the duration of the mission. Specifically, LunaH-Map needs to be able to have regular contacts with the ground during both the cruise and the science phase and such contacts need to allow for sufficient tracking time (the estimated need is between 4 and 6 hours per pass) as well as to download the entire amount of telemetry information and science data required by the mission.

As a result, one of the main requirements is the compatibility with the ground station network which for LunaH-Map is composed by the 34 m Deep Space Network (DSN) dishes located in Canberra, Madrid and Goldstone [3], plus the 21 m antenna at Morehead State University (MSU) [4].

Another important requirement is a downlink data rate greater than 100 Kbps during the science phase. As we will see in Section 3, a data rate of 256 Kbps can actually be achieved only using the DSN stations, while the MSU stations allows for 8 Kbps at lunar distance. It is important to notice that while currently the possibility of achieving 256 Kbps using DSN is sufficient to satisfy LunaH-Map telecommunication, upgrades are currently in progress at MSU to improve the receiving capability. Hence, the MSU station may be able to support 128 Kbps at lunar distance by the time LunaH-Map is launched.

Other requirements concern the frequency spectrum: LunaH-Map is in fact a NASA sponsored mission. As a result, LunaH-Map has to operate in the government X-Band Near Earth Band (8.45-8.5 GHz in downlink and 7.19-7.235 GHz in uplink). This affects the selection of the hardware components which have to be compatible with the spectrum regulation.

In terms of quality of service, the requirement is to maintain a minimum of 3 dB margin (for a Bit Error Rate of 10^-5) for both uplink and downlink at maximum range (1,002,900 Km) and with worst case antenna angle +/- 90 degree off boresight. This case is considered the safe mode, since no assumption is made on the pointing and the gain of the antenna is considered at its minimum (-10 dBi). Table XX summarizes the results for the safe mode and shows how the LunaH-Map design satisfied this requirement.

In terms of components design, the main requirement is to fit in the CubeSat form factor for volume, power and mass. This requirement is accomplished by selecting components specifically designed for CubeSats as described in Section 4 of this paper.

3. TELECOMMUNICATION ANALYSIS

Two main telecommunication analysis were performed for LunaH-Map at this stage of the development: link analysis and coverage analysis.

The link analysis aims to verify that the link can be closed between the spacecraft and the ground in several circumstances.

Link analysis assumptions for downlink and uplink are as follows:

- Spacecraft: transmitter power is 2 W, line losses at -1dB and peak gain at 7.16 dB. Pointing is considered very loose (conservative case) and the assumption is to be able to point at least into the 3dB beamwidth of the patch antenna (+/- 45 degree). Hence, the transmitting pointing loss is set at 3 dB.

- Ground stations: 2 type of ground stations are considered.

    - DSN 34 m dishes: for these ground stations all the assumptions are consistent with [3].

    - Morehead State University 21 m dish: for this dish an uplink power of 10 KW, waveguide loss of 1 dB, pointing loss of 0.5 dB and a noise temperature of 215K are assumed. These assumptions are slightly conservatives as the dish is currently being upgraded. Follow up papers will cover updated analysis on this dish.

- Path length: it is consistent with the trajectory simulations and it ranges between 1,002,900 Km (worst case) and the lunar distance (400,000 Km). It is worth noticing that the trajectory is constantly being updated. As a result, also this analysis is sensitive to changes in the path length.

- Waveform: BPSK modulation has been selected for both uplink and downlink. The uplink signal is uncoded. Turbo ½ coding is added on the downlink so as to lower the required Eb/N0 from 9.6 dB to 1.1 dB.

Results are shown in Table 1 and

Table 2for the downlink and in

Table 3 and

Table **4** for the uplink. For both the analysis, two cases are considered: the one at the farthest distance from Earth according to the trajectory (1,002,900 Km), and the one at the lunar distance (400,000 Km). These two points are in fact representative of the cruise phase and the science phase.

Table 1: Link analysis for downlink, using DSN, for maximum range and for lunar distance.

Item	Units	Downlink Maximum Range (DSN)	Downlink Lunar Distance (DSN)
Transmitter Power	dBW	3.00	3.00
Line Loss/Waveguide Loss	dB	-1.00	-1.00
Transmit Antenna Gain (net)	dBi	7.16	7.16
Equiv. Isotropic Radiated Power	dBW	9.16	9.16
Frequency	Ghz	8.49	8.49
Receive Antenna Diameter	m	34.00	34.00
Receive Antenna Gain	dBi	68.37	68.37
Propagation Path Length	km	1,002,990.00	400,000.00
Free Space Loss	dB	-231.05	-223.07
Transmit Antenna Pointing Loss	dB	-3.00	-3.00
Receive Antenna Pointing Loss	dB	-0.10	-0.10
Receive Antenna Pol. Losses	dB	-0.03	-0.03
Atmospheric Losses	dB	-0.17	-0.17
Implementation Losses	dB	-3.29	-3.29
Total Additional Losses	dB	-6.59	-6.59
Data Rate	bps	32,000.00	256,000.00
System Noise Temperature	K	29.60	29.60
SNR (Pt/N0)	dB - Hz	57.06	65.05
Modulation index	deg	77.00	77.00
Telemetry data suppression	dB	-0.23	-0.23
Ranging data suppression	dB	-0.83	-0.83
E_b/N_o	dB	7.66	6.61
E_b/N_o required	dB	1.10	1.10
Margin	dB	**6.56**	**5.51**

Table 2: Link analysis for downlink, using MSU, for maximum range and for lunar distance.

Item	Units	Downlink Maximum Range (MSU)	Downlink Lunar Distance (MSU)
Transmitter Power	dBW	3.00	3.00
Line Loss/Waveguide Loss	dB	-1.00	-1.00
Transmit Antenna Gain (net)	dBi	7.16	7.16
Equiv. Isotropic Radiated Power	dBW	9.16	9.16
Frequency	Ghz	8.49	8.49
Receive Antenna Diameter	m	21.00	21.00
Receive Antenna Gain	dBi	63.21	63.21
Propagation Path Length	km	1,002,990.00	400,000.00
Free Space Loss	dB	-231.05	-223.07
Transmit Antenna Pointing Loss	dB	-3.00	-3.00
Receive Antenna Pointing Loss	dB	-0.50	-0.50
Receive Antenna Pol. Losses	dB	-1	-1
Atmospheric Losses	dB	-0.17	-0.17
Implementation Losses	dB	-3.29	-3.29
Total Additional Losses	dB	-7.96	-7.96
Data Rate	bps	1,000.00	8,000.00
System Noise Temperature	K	215	215
SNR (Pt/N0)	dB - Hz	41.93	49.91
Modulation index	deg	77.00	77.00
Telemetry data suppression	dB	-0.23	-0.23
Ranging data suppression	dB	-0.83	-0.83
E_b/N_o	dB	7.58	6.53
E_b/N_o required	dB	1.10	1.10
Margin	dB	**6.58**	**5.43**

Table 3: Link analysis for uplink, using DSN, for maximum range and for lunar distance.

Item	Units	Uplink Maximum Range (DSN)	Uplink Lunar Distance (DSN)
Transmitter Power	dBW	43.00	43.00
Line Loss/Waveguide Loss	dB	-0.6	-0.6
Transmit Antenna Gain (net)	dBi	66.98	66.98
Equiv. Isotropic Radiated Power	dBW	109.38	109.38
Frequency	Ghz	7.23	7.23
Receive Antenna Gain	dBi	7.16	7.16
Propagation Path Length	km	1,002,990.00	400,000.00
Free Space Loss	dB	-229.66	-221.68
Transmit Antenna Pointing Loss	dB	-0.1	-0.1
Receive Antenna Pointing Loss	dB	-3.0	-3.0
Receive Antenna Pol. Losses	dB	-0.04	-0.04
Atmospheric Losses	dB	-0.17	-0.17
Implementation Losses	dB	-3.29	-3.29
Total Additional Losses	dB	-6.6	-6.6

Data Rate	bps	1,000.00	1,000.00
System Noise Temperature	K	460	460
SNR (Pt/N0)	dB - Hz	85.54	93.52
Modulation index	deg	1.5	1.5
Telemetry data suppression	dB	-2.06	-2.06
Ranging data suppression	dB	-3.01	-3.01
E_b/N_o	dB	51.69	59.67
E_b/N_o required	dB	9.6	9.6
Margin	dB	**42.09**	**50.07**

Table 4: Link analysis for uplink, using MSU, for maximum range and for lunar distance.

Item	Units	Uplink Maximum Range (MSU)	Uplink Lunar Distance (MSU)
Transmitter Power	dBW	33.00	33.00
Line Loss/Waveguide Loss	dB	-1.00	-1.00
Transmit Antenna Gain (net)	dBi	61.82	61.82
Equiv. Isotropic Radiated Power	dBW	93.82	93.82
Frequency	Ghz	7.23	7.23
Receive Antenna Gain	dBi	7.16	7.16
Propagation Path Length	km	1,002,990.00	400,000.00
Free Space Loss	dB	-229.66	-221.68
Transmit Antenna Pointing Loss	dB	-0.1	-0.1
Receive Antenna Pointing Loss	dB	-3.0	-3.0
Receive Antenna Pol. Losses	dB	-1	-1
Atmospheric Losses	dB	-0.17	-0.17
Implementation Losses	dB	-3.29	-3.29
Total Additional Losses	dB	-7.56	-7.56
Data Rate	bps	1,000.00	1,000.00
System Noise Temperature	K	460	460
SNR (Pt/N0)	dB - Hz	69.02	77.01
Modulation index	deg	1.5	1.5
Telemetry data suppression	dB	-2.06	-2.06
Ranging data suppression	dB	-3.01	-3.01
E_b/N_o	dB	35.17	43.16
E_b/N_o required	dB	9.6	9.6
Margin	dB	**25.57**	**33.56**

Results show that in downlink it is possible to close the link with a data rate of 32 Kbps for the cruise stage and of 256 Kbps for the science phase when using the DSN stations. When using the MSU station, the data rates drop to 1 Kbps at the farthest distance and to 8 Kbps during the science phase.

Results in uplink show that it is possible to close the link at 1 Kbps data rate at any point of the trajectory when using either DSN or MSU. Margins are really high in uplink which is very important given that pointing losses and tumbling scenario can always occur.

In addition to these cases, an analysis of the safe mode was developed. Safe mode analysis looks at the case in which the antenna is not pointing. In that particular case, the gain of the antenna drops to -10 dBi. The safe mode analysis verifies whether or not it is possible to close the link at the minimum data rate supported by the radio (62.5 bps) for both uplink and downlink. The analysis performed for the LunaH-Map mission confirmed the availability of plenty of margin at any point of the trajectory to allow for uplink and downlink at the minimum data rate without any pointing. Results are shown in Table 5 for the maximum range, which has to be considered a worst case scenario. It is possible to notice that in all these cases the margin is greater than 3dB.

Table 5: Safe mode summary table.

Case	Eb_N0 margin when using DSN	Eb_N0 margin when using MSU
Safe mode in downlink at maximum distance (Ranging on, no pointing, 62.5 bps data rate)	17.71 dB	4.36 dB
Safe mode in uplink at maximum distance (Ranging on, no pointing, 62.5 bps data rate)	39.95 dB	23.32 dB

Another analysis performed for the LunaH-Map telecommunication system is the coverage analysis. The objective of the coverage analysis is to gain a better understanding of the passes duration and range profile in function of the orbit. In fact, the range is highly variable across the entire LunaH-Map orbit, which means that not all the data rate modes can be supported at all times. The coverage analysis allows to identify, for the different ground stations used and for the different parts of the orbit, which data rates can be supported. For the coverage analysis, an STK simulation was setup, using the latest available orbit computed by the mission design team. Information from the link budget analysis were used to compute the maximum allowable data rate for each point of the trajectory and for the different ground stations (DSN and Morehead State University). The analysis was split between cruise and science phase. Results are shown in Figure 1, Figure 2, Figure 3, and Figure 4. For pointing, the analysis assumes to transmit and receive in the 3dB cone of the patch antenna which has

approximately a beamwidth of +/- 45 degrees. The DSN results shown are computed using the 34 m antenna in Goldstone, although simulations were also performed for Madrid and Canberra producing almost identical results.

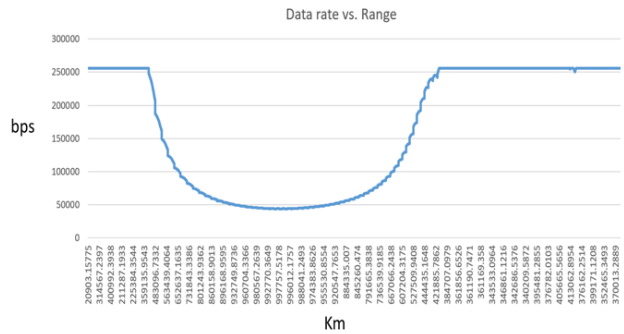

Figure 1: Data rate vs. range during cruise phase when using DSN 34 m dish.

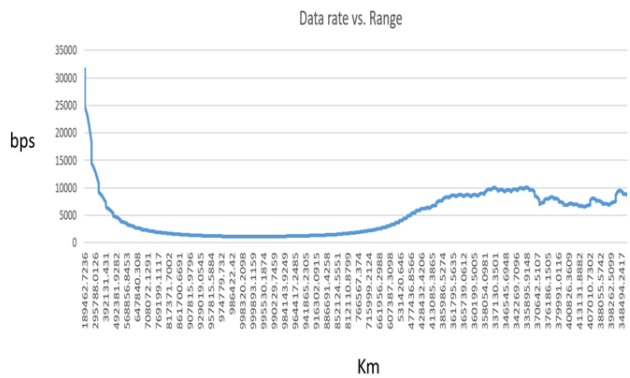

Figure 2: Data rate vs. range (zoomed plot) during cruise phase when using MSU 21 m dish.

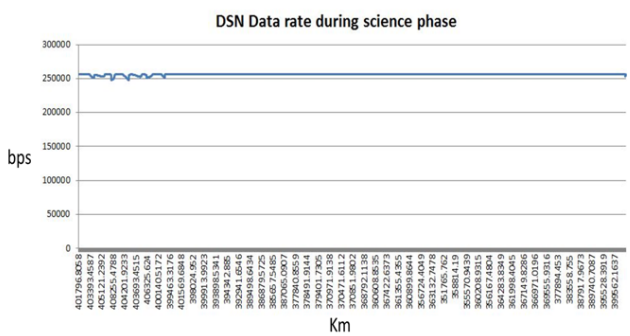

Figure 3: Data rate vs. range during science phase when using DSN 34 m dish.

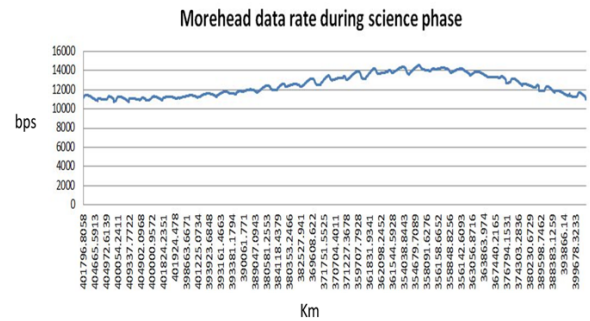

Figure 4: Data rate vs. range during science phase when using MSU 21m dish.

It is possible to observe that during the cruise stage the spacecraft quickly drifts farther from Earth until it reaches the maximum distance which is approximately 1,000,000 Km. At that distance, the link budget allows a supportable data rate of 32 Kbps when using DSN and of 1 Kbps when using the Morehead State University dish. As the spacecraft drifts away from the farthest orbital point to come back into lunar orbit, the distance between the spacecraft and the Earth is progressively reduced and the supportable data rate becomes 256 Kbps when using DSN and 8 Kbps when using MSU.

Length of contacts was also computed using the STK simulation environment, the orbital information and the ground station locations. Results are shown in Table 6 for DSN (Goldstone, Madrid, Canberra) and MSU.

Table 6: Summary of estimated contact length for DSN and MSU.

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

It is possible to observe that passes at MSU seems to be a little longer. This is partially due to the fact that the STK simulator already includes a mask for the DSN stations, while information on MSU mask are not yet available. Refined STK analysis will be performed when the information on MSU mask becomes available.

4. TELECOMMUNICATION COMPONENTS

The telecommunication subsystem design can be summarized in the diagram shown in Figure 5.

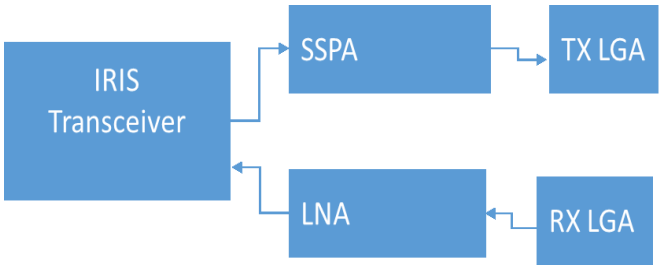

Figure 5: Telecommunication subsystem block diagram. The IRIS transceiver connects to the SSPA and the TX LGA for transmission and to the LNA and the RX LGA for reception.

The transceiver used for the mission is the JPL IRIS radio. The IRIS radio [5] (shown in Figure 6) allows for telecommunication and navigation support at X-Band Near Earth and Deep Space frequencies. It provides coherent and uncoherent uplink and downlink, BPSK modulation with different coding options (Reed Solomon, convolutional, turbo). It is also CCSDS compatible which allows for it to be used with the Deep Space Network. IRIS has been developed by JPL for previous CubeSat missions such as INSPIRE and MarCO. The IRIS designed for LunaH-Map missions is a slightly modified version of the MarCO design since it allows for a 2W SSPA instead of a 4W SSPA. This feature is very important for LunaH-Map as it allows to reduce the power consumption which is very critical for the mission, especially given the long tracking passes (4-6 hours).

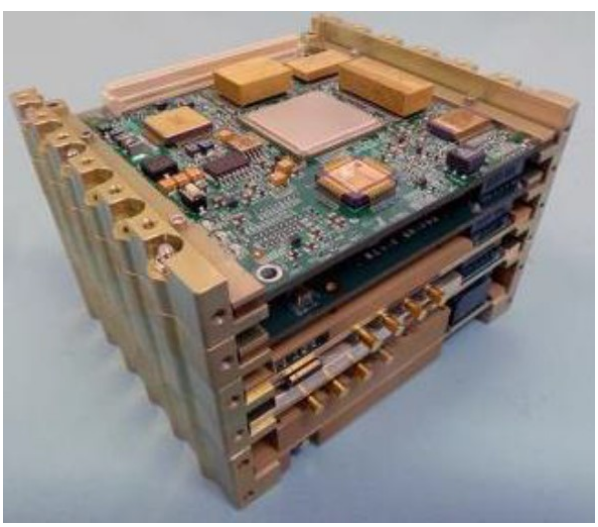

Figure 6: IRIS radio [5].

The IRIS radio is connected to the low noise amplifier and to the two receiving low gain patch antennas. The radio is also connected to the 2 W solid state power amplifier and to the two low gain transmitting patch antennas. The antennas are patches, right-handed circularly polarized, 50 Ohm impedance and 7.16 dBi peak gain. The antennas are placed on opposite side of the spacecraft to guarantee better coverage for the spacecraft. The switching mechanism will be regulated by the flight software.

The total mass of the telecommunication system is estimated to approximately 1.3 Kg and the peak power consumption in full transmitting/receiving mode is approximately 25 W.

5. Integration and Test

The patch antennas are currently being manufactured and tested at JPL. The IRIS radio, SSPA and LNA are currently in development. Before integration in the spacecraft, the radio and the amplifier will be extensively tested to measure: frequency, bandwidth, output power, radio telemetry, radio command, coherency, ranging, noise figure, uplink and downlink waveforms.

After the tests on the radio and the antennas are completed, the components will be integrated on the LunaH-Map spacecraft at Arizona State University. Environmental tests will take place at Arizona State University and they will be performed at the CubeSat level. End to end compatibility test between the spacecraft and the DSN will be performed at JPL.

6. Summary Future Work

The paper describes the initial steps in the design and implementation of a telecommunication subsystem for LunaH-Map, one of the first interplanetary CubeSat missions to be launch on EM-1. The paper contains an overview of the main telecommunication requirements. The telecommunication analysis detailed in the paper shows that the design is able to provide up to 256 Kbps data rate capability with more than 3 dB margin. The analysis includes data rate and coverage profiles for the entire duration of the LunaH-Map mission showing that it is possible, at lower data rate, to close the link at any point of the trajectory. Safe mode analysis shows that it is possible to transmit and receive at the lowest IRIS supported data rate (62.5 bps) at any point of the trajectory, even when doing ranging and without pointing. Finally, coverage analysis shows that the duration of contacts is sufficient to satisfy the need for 4-6 hours passes.

LunaH-Map telecommunication subsystem components have been selected. They are currently in development and work is ongoing to prepare for performance characterization tests. Integration in the spacecraft will take place soon after, right before the start of the environmental testing campaign.

Since interplanetary CubeSat missions are new, many aspects of the telecommunication design are sometimes in flux. However, LunaH-Map telecommunication subsystem design has now reached a good level of maturity, passed the preliminary design review and the peer review. The telecommunication subsystem development is currently focused on components manufacturing and tests, frequency coordination, NTIA filing, and ground station coordination. The critical design review is expected to take place at some point toward the end of the 2016 calendar year,

ACKNOWLEDGEMENTS

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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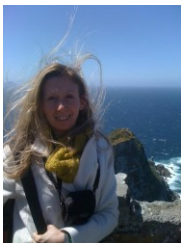
BIOGRAPHY



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Craig Hardgrove *received is an Assistant Professor in the School of Earth and Space Exploration at Arizona State University. He is the Principal Investigator for the Lunar Polar Hydrogen Mapper (LunaH-Map) mission, as well as a Participating Scientist on the Mars Science Laboratory Curiosity rover mission as a member of the Dynamic Albedo of Neutrons instrument team. On Curiosity, Craig uses neutron, geochemical, and stratigraphic data to derive clay and hydrated mineral phase abundances in the shallow subsurface throughout Curiosity's traverse in Gale Crater. Craig is also working to develop new neutron and gamma-ray spectrometer instrumentation for use on future planetary science missions. Craig is also the director of research for the ASU NewSpace Initiative, which is working to partner academia with the private commercial space industry*

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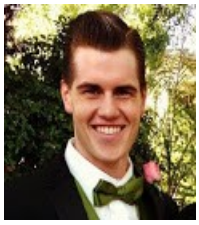

Jim Crowell *is a PhD student in the School of Earth and Space Exploration, developing extreme environment technologies for scientific exploration in deep sea, volcanic, and polar regions of Earth as well as deep space, lunar orbit, and on the surface of the Moon.*

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