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The Lunar Polar Hydrogen Mapper (LunaH-Map) Mission

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ABSTRACT

The Lunar Polar Hydrogen Mapper (LunaH-Map) mission will map hydrogen enrichments within permanently shadowed regions at the lunar south pole using a miniature neutron spectrometer. While hydrogen enrichments have been identified regionally from previous orbital missions, the spatial extent of these regions are often below the resolution of the neutron instruments that have flown on lunar missions. LunaH-Map will enter into an elliptical, low altitude perseline orbit which will enable the mission to spatially isolate and constrain the hydrogen enrichments within permanently shadowed regions. LunaH-Map will use a solid iodine ion propulsion system, X-Band radio communications through the NASA Deep Space Network, star tracker, C&DH and EPS systems from Blue Canyon Technologies, solar arrays from MMA Designs, LLC, mission design and navigation by KinetX. Spacecraft systems design, integration, qualification, test and mission operations are performed by Arizona State University.

MISSION OVERVIEW

There is renewed interested in lunar exploration and, in particular, in a more detailed characterization of hydrogen-rich regions at the lunar south pole that have been identified by previous NASA planetary science missions to the Moon. The LunaH-Map mission, selected by NASA's Science Mission Directorate in late-2015, will make neutron measurements from a low altitude perilune orbit to help place important constraints on our understanding of the distribution of lunar polar volatiles within permanently shadowed regions (PSRs). The LunaH-Map spacecraft is designed to fit within a 6U+ CubeSat form factor carrying one science instrument, a new type of neutron spectrometer. A new type of detector material is used, as this was required to achieve sufficient efficiencies for neutron detection in such a small volume. In order to improve upon the spatial resolution achieved by previous neutron instruments at the Moon, LunaH-Map will achieve perilune altitudes between 10 – 15 km above the lunar surface.

Science

Since the detection of enhanced hydrogen at the lunar poles by the Lunar Prospector Neutron Spectrometer (LPNS) in 1998, there has been significant and continued interest in the nature and distribution of volatiles at the Moon and in other solar system bodies [1]. The detection of reduced epithermal neutron flux at the poles by neutron experiments on board the Lunar Prospector (LP) spacecraft and the Lunar Reconnaissance Orbiter (LRO) provided positive identification of increased hydrogen concentrations in PSRs, likely in the form of water-ice [1, 2].

The LP and LRO missions used neutron spectrometers from orbit to map bulk hydrogen distributions at the lunar poles [1, 2]. Neutron spectrometers measure hydrogen (which is bound in water ice and other hydrated mineral phases) within the top meter of the lunar surface by detecting the neutrons created by interactions with high energy galactic cosmic rays that interact with lunar regolith and subsequently leak out of the surface. The energy distribution of neutrons leaking out of lunar surface will be a function of the bulk geochemistry, hydrogen abundance, depth distribution of hydrogen and a variety of other factors related to the regolith and surface properties [3, 4]. Neutrons in the energy range of ~0.4 eV to ~10 keV will be most sensitive to hydrogen abundance and have been used to map quantities of hydrogen down to ~50 ppm [5]. From orbit, however, neutron detectors typically have poor spatial resolution, with an effective field of view of about one and a half times the orbital altitude [4]. Previous missions have orbited at altitudes of tens to hundreds of kilometers, resulting in coarse (many kilometer-scale) maps of neutron counts [1, 2]. These maps are sufficient to reveal the regional hydrogen distribution at the poles but are not high enough resolution to reveal distributions of hydrogen enrichments within PSRs. Higher spatial resolution neutron maps of these regions (at scales of 10 – 20 km) may reveal enrichments of water ice within the PSRs. These maps would place important constraints on lunar volatile emplacement and lunar polar wander as well as help future mission planning (landing site selections) at the lunar south pole.

The maps of hydrogen enrichments that will be produced by LunaH-Map are a function of the science orbit, the altitude above terrain, the neutron detector response, the surrounding lunar topography, and the hydrogen content of the lunar surface that passes within the detector's sensing area each orbit. Preliminary analysis of LunaH-Map's ability to resolve lunar PSRs is shown in Figures 1 and 2. Figure 1 shows a subset of the LunaH-Map ground tracks where even small (<10 km) PSRs are nearly resolved (black arrow). Figure 2 shows that the PSRs are not fully resolved (fully resolved PSRs have a contribution of 1); however, some fine scale features are prominent near periapsis.

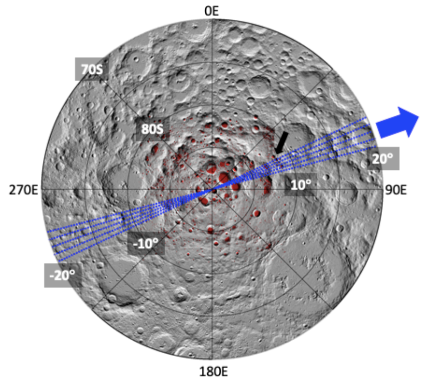

Figure 1: LunaH-Map science phase ground tracks (in blue) superimposed on Moon LRO LOLA Hillshade 237m (v4, LOLA Science Team, retrieved from USGS web site). PSRs are labeled in red as defined in Mazarico et al., 2011.

Trajectory

An innovative trajectory and mission profile has been designed in order to safely deliver the LunaH-Map spacecraft into a final lunar orbit that will fulfill the mission objectives [6]. The trajectory is partitioned into three primary phases; an Earth-Moon transfer phase, lunar orbit transition phase, and science phase, each of which presents unique challenges.

The Earth-Moon transfer phase begins with the spacecraft's deployment from the SLS EM-1 Interim Cryogenic Propulsion Stage (ICPS) host vehicle at a distance from Earth of ~70,000 km. This insertion state was favorable as it occurs after the ICPS has exited the Van Allen Radiation Belts, but early enough to allow time for telemetry, tracking, and propulsive maneuvers prior to the first lunar flyby, labeled Periselene-1.

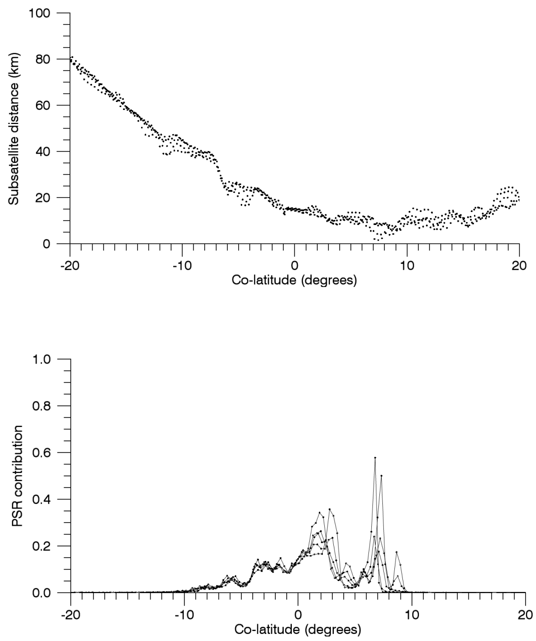

Figure 2: top) LunaH-Map altitude above terrain vs latitude along each blue ground-track shown in Figure 1. Bottom) Contribution to the observed neutron count rate by PSRs for the ground-tracks shown in Figure 1.

Periselene-1 is used to contain the spacecraft within the Earth-Moon system and target the Sun-Earth weak stability boundary (WSB) which allows for a low-energy transfer from Periselene-1 to Lunar orbit insertion. This nominal transfer trajectory includes one loop around the Earth with perigee > 100,000 km altitude to avoid the Van Allen Belts and concludes with a set of maneuvers to targets weak capture and orbit insertion at the second lunar encounter, Periselene-2.

After weak capture, the lunar orbit transition phase begins with a set of maneuvers that ensures the spacecraft is captured in a stable lunar orbit. After "strong capture," a long cadence of maneuvers spanning several months are executed to reduce the orbital energy and eventually enter into the final science orbit. These maneuvers will occur contiguously when the spacecraft is not in eclipse nor communicating with ground stations and burn updates will occur at regular intervals to ensure the transition profile is maintained. If necessary, the spacecraft may enter a stable circular orbit during its transition to avoid Earth eclipses before targeting the final science orbit. After maneuvering for several months, the spacecraft's orbital parameters will eventually match those of the final desired science orbit. An illustrated view of the transition from weak lunar capture to elliptical science orbit is shown in **Figure 3**.

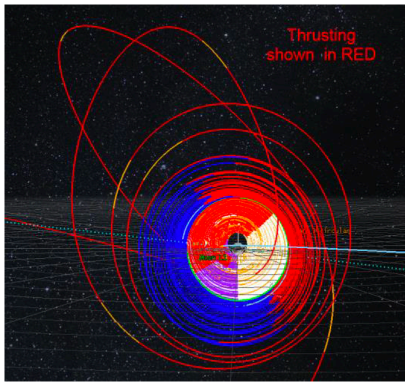

Figure 3: *LunaH-Map Transition Phase*. Earth-centered view of LunaH-Map transition from weak lunar capture to elliptical science orbit.

An elliptical science orbit with periselene above the lunar south pole will then be maintained with deterministic orbit adjustment maneuvers occurring at apolune. The periselene altitude of each pass above the south pole will be between 5-25 km, enabling productive scientific return. This science orbit will be maintained for at least 282 lunar orbits (46 days), with the possibility of extending the operations and orbital maintenance if desired. The trajectory design was constrained such that maneuvers are aligned in the velocity or anti-velocity direction and may not occur on consecutive orbits, due to operations constraints. This results in approximately 60 orbits requiring deterministic maneuvers to maintain the desired elliptical orbit. The elliptical science orbit is illustrated in **Figure 4**.

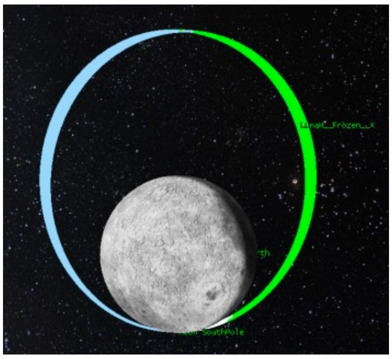

Figure 4: *LunaH-Map Science Phase*. A moon-centered view of the highly elliptical science orbits.

SPACECRAFT SUBSYSTEMS

Miniature Neutron Spectrometer

The Miniature Neutron Spectrometer (Mini-NS) uses a set of CLYC scintillators to detect neutrons and has been designed with a gadolinium shield to provide sensitivity primarily to neutrons above 0.5 eV. The Mini-NS (**Figure 5 left**) consists of two detectors that are comprised of four modules (or sensors), shown in **Figure 5 right**. The modules consist of a hermetically sealed CLYC (Cs_2LiYCl_6) scintillator in an aluminum can, and the design provides 200 cm^2 of the scintillator's area facing the Moon. The sensors are encased with a 0.5 mm layer of gadolinium. The readout electronics are separated into two sections, where the analog components are placed near the detector and the digital electronics are further away. The digital readout electronics are mounted to the exterior support frame of the instrument, where the heat generated in these electronics is directly dissipated to the spacecraft chassis. The instrument interfaces with the spacecraft via RS422, providing a per second heartbeat to monitor the instrument health. Data products are stored locally on the instrument, as the real time is issued by the spacecraft to co-register the data to the spacecraft trajectory. Event data from each PMT is tagged and individual module values (gain, bias voltage, pulse shape analysis parameters) can be adjusted in flight. Each electronics board can operate up to 4 Mini-NS modules and future missions can customize the number of Mini-NS modules based on the science mission requirements and configure them based on the spacecraft mass, power and volume constraints. The mass of the flight Mini-NS instrument (8 modules, 2 electronics board assemblies, mechanical structure) is 3.4 kg with an estimated power draw of 9.6 W. In stand-by mode, the spacecraft will interface with the instrument to transfer data or to initiate data acquisition, where the power draw in this state is estimated to be 3.6 W.

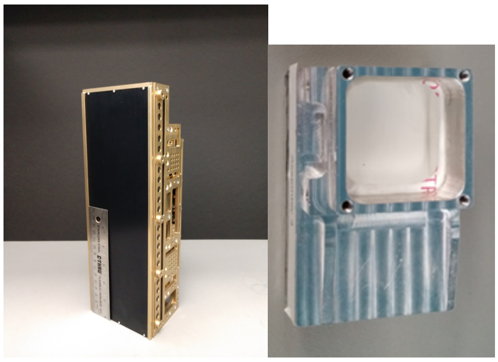

Figure 5: left) The flight Mini-NS with ruler for scale; right) A single Mini-NS detector module without PMT mounted. Up to four detector modules can be operated by one electronics board assembly. The Mini-NS consists of 8 detector modules, which operate as two independent 2x2 detector arrays.

Telecommunication

The telecommunication system for LunaH-Map is based on previously developed JPL hardware for other interplanetary CubeSat missions such as INSPIRE [7] and MarCO [8]. The key component of the telecommunication system is the Iris radio which provides support for telemetry, command and navigation functions. It operates at the Near-Earth X-Band frequency range (7145-7190 MHz for uplink, 8450-8500 MHz for downlink), and provides coherent transmission with an 880/749 turn around ratio to support ranging. Uplink modulation is PCM/PSK/PM, NRZ with BCH encoding and data rates ranging from 62.5 bps to 8 Kbps. Specifically, LunaH-Map selected uplink data rates are 62.5 bps (safe mode) and 1 Kbps (nominal mode). Downlink modulation is BPSK with options for RS (255,223), convolutional (K=7, r=1/2) or turbo encoding (1/2,1/3,1/6 with 1784 or 8920 bit frames) and data rates ranging from 62.5 to 256 Kbps. LunaH-Map will use 62.5 bps (safe mode) and a set of nominal mode data rates ranging from 1 Kbps to 128 Kbps. The choice of downlink data rates will depend on the phase of the mission (deployment vs. cruise, vs. science phase), the ground station used (either the 34 m dish at DSN, or the 21 m dish at Morehead State University), and the specific pointing capabilities of the spacecraft during the different mission phases. The encoding solutions implemented will mostly be alternating between Turbo ½ and Turbo 1/6, depending again on mission phase and ground station used.

The Iris radio is connected in the receiving path to the Low Noise Amplifier (LNA), and the LNA is then connected to two 6 dBi patch antennas placed on opposite side of the spacecraft for coverage maximization. In the transmitting path, the Iris radio is connected to the Solid State Power Amplifier (SSPA) which provides 2 W of amplification. The 2 W radio frequency signal is then transmitted through other two 6 dBi patch antennas which are placed also on opposite sides of the spacecraft.

In terms of ground support, LunaH-Map will use the services of the DSN (Deep Space Network) and in particular the 34 m antennas at Goldstone, Canberra, Madrid, and the new 21 m antenna at Morehead State University (Cheung, K.M. 2015) which is now DSS number 17 and part of the NASA DSN complex. Link and coverage analysis have been performed to assess the data rate capabilities at different points of the mission. The data rate capabilities and range variation when using DSN and when using the 21 m antenna at Morehead State University are shown in **Figure 8.**

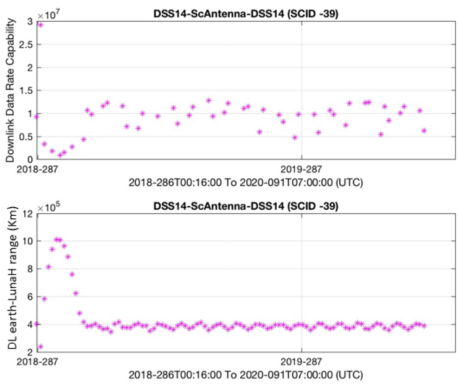

Figure 8: Data Rate capabilities and range for LunaH-Map mission when using DSN antennas.

Propulsion

LunaH-Map is equipped with an electric propulsion (EP) system for orbit transfer and station keeping. Developed by Busek Co. Inc., the BIT-3 (Busek Ion Thruster – 3 cm grid) propulsion system uses solid-storable iodine as propellant, a pioneering technology that can enable a wide variety of deep-space CubeSat missions [9, 10]. The ability to use iodine as propellant is a game-changer for CubeSat propulsion, because iodine can be stored as a dense solid (4.9g/cc), and its torr-level storage and operating vapor pressure is safe to launch while allowing for very lightweight and conformal tanks. In contrast, legacy EP propellant xenon has to be stored as highly compressed gas (>2,000psi) and requires bulky, spherical-shaped pressure vessels that are unfavorable for a CubeSat's unique form factors. Busek's BIT-3 ion thruster and its complementary cathode neutralizer also hold the distinction of being the world's first EP device ever to fire on iodine propellant (**Figure 9**), and its performance has been verified on the ground via direct thrust measurement.[i]

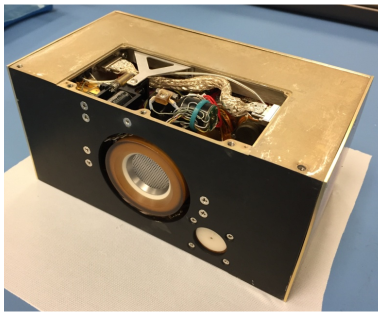

Figure 9: Fully integrated BIT-3 iodine ion propulsion system (left) and demonstration of continuous, steady-state firing at nominal 70W input power

Power

To meet or exceed the requirements of the LunaH-Map mission, MMA designed an eHaWK™ (Enhanced High Watts Per Kilogram) solar array which leveraged high TRL-8 HaWK design components to produce an estimated 96 watt at beginning of life (BOL). MMA's solution can be stowed efficiently in a2Ux3Ux10mm volume. The LunaH-Map eHaWK™ incorporates proven cell performance with the XTJ prime cells manufactured by Spectrolab, Inc. These cells have an average efficiency of 30.7%, with an active area of 27.22 cm^2. They are protected by 5 mil (127 micron) cerium-doped coverglass with an anti-reflective coating. Spectrolab measures the electrical performance of each CIC using a steady-state solar simulator and this data is used by MMA Design to design each string assembly and provide similar performance across all strings. The LunaH-Map eHaWK™ integrates a discrete bypass diode at the CIC level for reverse bias protection. Each string of 7 cells in series also includes a single blocking diode for string protection.

The LunaH-Map eHaWK™ incorporates MMA's patented CubeSat Solar Array Drive Assembly (SADA). This facilitates higher average orbital power and enables peak power tracking. The SADA features +/-180-degrees of actuation, up to 16 signal/power feed-through conductors per wing, and actuation speeds up to 0.188 revolutions per minute.

Avionics, Control, Command and Data Handling

Blue Canyon Technologies is providing the spacecraft avionics for the LunaH-Map mission. The BCT provided avionics include the LunaH-Map Guidance, Navigation, & Control Subsystem (GN&C), the Command & Data Handling Subsystem (C&DH), and the Electrical Power Subsystem. BCT is utilizing the heritage XB1-50 avionics suite to provide the GN&C and C&DH subsystems with a heritage Power Subsystem including a battery and power switching board. The BCT XB1-50 avionics provide a complete bus solution in a highly integrated, precision spacecraft platform. The LunaH-Map avionics provides a unified, tested package that leverages BCT's GN&C expertise and experience to provide solutions to the unique requirements of the LunaH-Map mission.

The LunaH-Map XB1-50 avionics include flexible interfaces, precise 3-axis attitude determination & control provided by a BCT-designed star tracker, low jitter BCT Reaction Wheels, torque rods and integrated control algorithms. The attitude control system enables precise orbit propagation of multiple objects enabling pointing with the Inertial, Earth or Lunar Reference frames. The XB1-50 enables bus functionality for GN&C, EPS, Thermal, C&DH, RF Communication, Data Storage and Flight Software, and control of the LunaH-Map propulsion system and solar array drive assembly. In addition, the system enables autonomous fault protection with the unique capability to recover from a spacecraft processor reset and autonomously resume a critical spacecraft burn, and utilizes Deep Space Algorithm heritage obtained from the successful MarCO spacecraft.

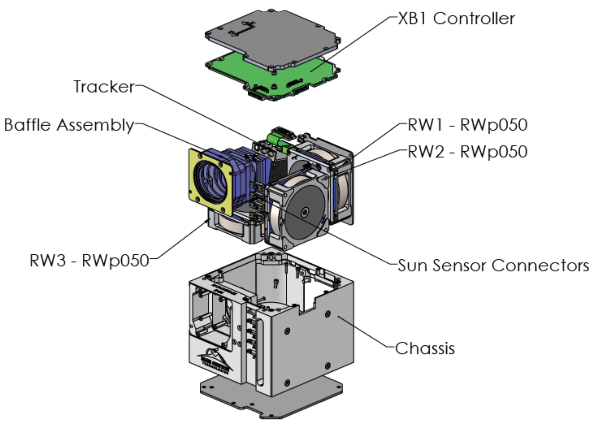

Figure 11: Exploded View of BCT XB1-50 Avionics Module for LunaH-Map

OPERATIONS

Mission operations for the LunaH-Map program, including spacecraft command and control, telemetry processing and analysis, science data retrieval, archiving and product generation, and mission planning and scheduling, is performed on-campus at ASU. ASU's state-of-the-art Mission Operations Center is a multi-mission facility that will also house operations for components of the Mars 2020 rover and Psyche asteroid missions. For downlink operations, telemetry from the spacecraft is transmitted over X-Band via the Iris transponder, and received by the DSN. The DSN forwards the telemetry to ASU over a VPN connection where it is processed by the JPL-developed AMMOS Instrument Toolkit (AIT) Ground Data System. Throughout each satellite contact, real-time data from the spacecraft is downlinked for graphical trending and analysis for state of health monitoring purposes. Additional stored flight software and spacecraft state of health telemetry is available for immediate analysis by the engineering and science teams, while the science data is labeled and archived following Planetary Data System (PDS) standards. Following the satellite contact, custom data products are generated for the science, engineering, and KinetX mission planning teams. KinetX receives attitude prediction and history files, as well as thruster firing history and a predicted events file; these are used to generate spacecraft ephemeris reconstruction and prediction files, navigation tracking requests, maneuver interface files, and light time files, which are all incorporated in to the mission operations planning cycle. Similarly, the engineering and science teams use their data products to generate calibration or instrument requests to submit to the planning cycle, as necessary.

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