The Lunar Polar Hydrogen Mapper (LunaH-Map) Mission

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LunaH-Map Mission Overview

- NASA SMD SIMPLEx 2015 mission led by ASU
- 6U+ CubeSat form factor to launch on SLS EM-1
- **Science Objective:** Map hydrogen enrichments within PSRs at the lunar south pole at spatial scales <20 km²
- **Tech Objectives:** Deep space navigation and operations using ion propulsion on a small sat
Hydrogen Distributions from Neutron Spectroscopy

- Neutron measurements are sensitive to **bulk** hydrogen distributions at 1 meter depth
- Uncollimated neutron detector ‘footprints’ are approximately 1½ times orbital altitude
- Lunar hydrogen abundances within PSRs broadly ranging from 200 ppm up to almost 40 wt% could be consistent with LPNS data depending on spatial distribution, extent of coverage, and burial depth [Lawrence et al 2006].

*Feldman et al., Science, 281, 1496, 1998*
Pixon-based reconstruction of LPNS data (Elphic et al 2007) reveals high WEH abundances in Cabeus (near 1 wt%) and lower abundances in Shoemaker, Haworth, and Faustini (~0.3 wt%).

Analysis of LEND data (Sanin et al 2017) reveals higher WEH abundances (~0.5 wt%) in south polar craters Shoemaker, Haworth, and Faustini.

Figure 1 Map of current day ice stability depth from Siegler et al [2015] as used in constraint map development.
Trajectory Design

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>4.76 hour</td>
</tr>
<tr>
<td><strong>Aposelene Altitude</strong></td>
<td>3150 km</td>
</tr>
<tr>
<td><strong>Periselene Altitude</strong></td>
<td>RAAN dependent 15-25 km</td>
</tr>
<tr>
<td><strong>Inclination</strong></td>
<td>90°</td>
</tr>
<tr>
<td><strong>Argument of Periselene</strong></td>
<td>273.5°</td>
</tr>
</tbody>
</table>

Day in the Life - Science

- Tracking/Communication
- Statistical aposelene maneuver (every 3-5 days)
- Mini-NS active ~30 min centered around perilune
- Tracking/Communication
- Eclipse (beta angle dependent) – no operations
Science Phase

- Period: 4.76 hour
- Aposelene Altitude: 3150 km
- Periselene Altitude: RAAN dependent, 15-25 km
- Inclination: 90°
- Argument of Periselene: 273.5°

Example orbital data

High spatial resolution achieved near periapsis

LOLA PSRs
(Mazarico et al., 2011)

Data superimposed on Moon LRO LOLA Hillshade 237m v4, LOLA Science Team, retrieved from USGS web site
Neutron Measurements of the Moon

Science
• Low-altitude (< 20 km) uncollimated measurements of lunar neutrons will:
  • Determine the bulk hydrogen content and depth within PSRs (at spatial scales of < ~35km)
• These data will:
  • Constrain sources and sinks for polar volatiles
  • Constrain models of lunar polar wander
  • Identify landing sites for future landed missions at the lunar South Pole
  • Complement LP-NS and LRO LEND neutron data

Requirements
• To determine bulk hydrogen abundance, LunaH-Map needs to measure only epithermal neutrons:
  • Short mission duration requires a large (200 cm²) and efficient detector array
  • Ability to discern signal from background and custom electronics to count neutrons once per-second
  • No off-the-shelf solution available, so we developed, built and calibrated our own Miniature Neutron Spectrometer (Mini-NS)
Increased hydrogen suppresses epithermal neutrons ($E > 0.4$ eV) and increases thermal neutrons ($E < 0.4$ eV).

LunaH-Map’s signal is the difference between dry epithermal count rate and enriched epithermal count rate.
Neutron Sensitive Materials

- Neutron Capture Isotopes: $^3$He, $^6$Li, $^{10}$B
  - $^3$He: noble gas, proton, triton 0.75 MeV
  - $^6$Li: alkali metal, alpha, triton 4.8 MeV
  - $^{10}$B: metalloid, alpha, $^7$Li, g (94%) 2.8 MeV

Detector materials

- He-3 Tube
- Li-Glass
- Boron-Loaded Plastic
- CLYC
Efficiency of 2-cm thick CLYC matches LPNS 5.7-cm diameter He-3 counter.
Detection Area

LPNS

• Effective area of one LPNS He-3 tube is ~100 cm$^2$.
• He-3 tube gas pressure 10 atm, ~0.0014 g/cm$^3$
• Epithermal count rate ~20 s$^{-1}$.

Mini-NS

• Total area of eight Mini-NS CLYC modules is ~200 cm$^2$.
• CLYC density ~3.3 g/cm$^3$
• Epithermal count rate ~40 s$^{-1}$.
Modeling of Expected Count Rates

- Using lunar neutron input spectrum from 10 km altitude
Simulation maps made from 15 x 3150 km science orbit. Basemap combines LEND high H regions (Sanin et al., 2017) and the Shackleton enrichment from pixon-reconstructed LPNS data (Elphic et al, 2007) to illustrate the type of map LunaH-Map will be able to create (West et al., LPSC 2017).
Miniature Neutron Spectrometer for CubeSats and SmallSats

CLYC Module

Instrument Housing and Electronics

Individual CLYC module, PMT and housing (x8)

Thermal

Epithermal

Fast
Mini-NS Flight Unit

Mini-NS: Miniature Neutron Spectrometer
Miniature Neutron Spectrometer for CubeSats and SmallSats – Flight Unit

*Mini-NS Flight Unit delivered and calibrated at Los Alamos National Lab Neutron Free In-Air (NFIA) facility in late Fall 2018*

<table>
<thead>
<tr>
<th>Detector</th>
<th>2x4 array of CLYC (elpasolite scintillator, Cs₂LiYCl₆:Ce) crystals, each crystal 4 cm x 6.3 cm x 2 cm</th>
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<tbody>
<tr>
<td>Dimensions</td>
<td>25 cm x 10 cm x 8 cm</td>
</tr>
<tr>
<td>Mass</td>
<td>3.3 kg</td>
</tr>
<tr>
<td>Power</td>
<td>10W</td>
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<tr>
<td>Data Acquisition</td>
<td>Counts binned every 1 sec</td>
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</table>
Mini-NS calibration team at Los Alamos National Laboratory Neutron Free In-Air Facility – December 2018

left to right: Lena Heffern (ASU), Erik Johnson (RMD), Tom Prettyman (PSI), Joe DuBois (ASU), Richard Starr (NASA GSFC), Bob Roebuck (AZST), Katherine Mesick (LANL), Graham Stoddard (RMD), Craig Hardgrove (ASU)
Mini-NS Module Demonstration

Detector and PMT module on left, digital and analog board on right

- 1 Mini-NS module, analog and digital board delivered May 13th to U. Hawaii for NEUTRON-1 3U CubeSat
- NEUTRON-1 will enter LEO on an ISS resupply flight in late 2019

<table>
<thead>
<tr>
<th></th>
<th>1 Module</th>
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<tbody>
<tr>
<td>Mass</td>
<td>396 g</td>
</tr>
<tr>
<td>Power</td>
<td>5 W</td>
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LunaH-Map Spacecraft

- **Mini-NS Instrument**
- **LGA**
- **Separation Connector**
- **BIT-3 Thruster**
- **LGA**
- **Coarse Sun Sensor**
- **BCT XB1-50 / Star Tracker**
- **Solar Array Hold Down Arms**
- **Primary Coarse Sun Sensor**
- **Single Axis Solar Array Drive**

**Spacecraft Specs**

<table>
<thead>
<tr>
<th>Dimension: (stowed)</th>
<th>10x20x30cm</th>
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<tbody>
<tr>
<td>Mass</td>
<td>14 kg</td>
</tr>
<tr>
<td>Power</td>
<td>90W BOL 56W-hr Battery</td>
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<tr>
<td>Propulsion</td>
<td>Busek BIT-3 Ion Thruster</td>
</tr>
<tr>
<td>Comm.</td>
<td>JPL Iris Deep Space Transponder</td>
</tr>
<tr>
<td>C&amp;DH / GN&amp;C</td>
<td>BCT XB1-50</td>
</tr>
</tbody>
</table>
LunaH-Map MMA eHawk+ Flight Solar Arrays – Delivered February 2019
LunaH-Map
Flight Iris radio – Delivered
February 2019
LunaH-Map Flight BIT-3

BIT-3 QM Hot Fire Iodine Testing
MOC co-located in ASU’s shared operations facility
JPL AIT for spacecraft uplink and downlink
KinetX provides mission navigation
ASU science/instrument ops development coincident with Mars 2020 and Psyche missions
All subsystem EM units delivered and integrated into the LunaH-Map flatsat (labeled in image)

On schedule for delivery in mid-March 2020

Current Engineering Team Activities
- Electrical I&T of flight units,
- EM unit testing
- Developing AIT command/telemetry tools
Road to Launch

- Initial Accommodation Audit – completed on December 11, 2015
- Delta IAA – completed on February 24, 2016
- System Requirements Review – completed on April 8, 2016
- Phase 1 Safety Review – completed on June 21, 2016
- Preliminary Design Review – completed on July 25, 2016
- Critical Design Review – completed June 29, 2017
- Phase 2 Safety Review – completed on November 9, 2017
- Systems Integration Workshop – completed on December 7, 2017
- Flight Instrument Delivery – November 8, 2018
- Flight Solar Array Delivery – February 22, 2019
- Flight Radio Delivery – March 20, 2019
- Enter Assembly, Integration, and Test – Q1 2019
  - AI&T Review/Workshop with review board – completed on December 7, 2017
- Flight Propulsion Delivery – scheduled September, 2019
- Flight GNC and C&DH System – scheduled mid-August, 2019
- Phase 3 Safety Review – scheduled on September 25, 2019
- Spacecraft Delivery to Tyvak – scheduled on mid-March 2020
- Launch-SLS EM-1 – scheduled on ~Nov, 2020

LunaH-Map Program Milestones to Date

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
<th>Status</th>
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<tr>
<td>IAA</td>
<td>11 December 2015</td>
<td>Δ-IAA REQUIRED</td>
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<tr>
<td>Δ-IAA</td>
<td>24 February 2016</td>
<td>PASSED with RFAs</td>
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<tr>
<td>SRR</td>
<td>8 April 2016</td>
<td>PASSED with RFAs</td>
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<tr>
<td>I-PDR</td>
<td>9 June 2016</td>
<td>PASSED with RFAs</td>
</tr>
<tr>
<td>Phase 1 SR</td>
<td>21 June 2016</td>
<td>PASSED</td>
</tr>
<tr>
<td>M-PDR</td>
<td>25 July 2016</td>
<td>PASSED with RFAs</td>
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<tr>
<td>CDR</td>
<td>29 June 2017</td>
<td>COMPLETED</td>
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<tr>
<td>Phase 2 SR</td>
<td>9 Nov 2017</td>
<td>COMPLETED</td>
</tr>
<tr>
<td>Integration Workshop</td>
<td>7 Dec 2017</td>
<td>COMPLETED</td>
</tr>
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Review Board Members: Dr. Andrew Klesh, Jet Propulsion Laboratory (Review Board Chair), Dr. Thomas Werne, JPL, Dr. Travis Imken, JPL, Dr. Juergen Mueller, JPL, Dr. Eric Gustafson, JPL, Dr. Thomas Prettyman, Planetary Sciences Institute, Dr. James Bell, Arizona State University, Dr. Jordi Puig-Suari, California Polytechnic State University, Richard Elphic, NASA Ames.