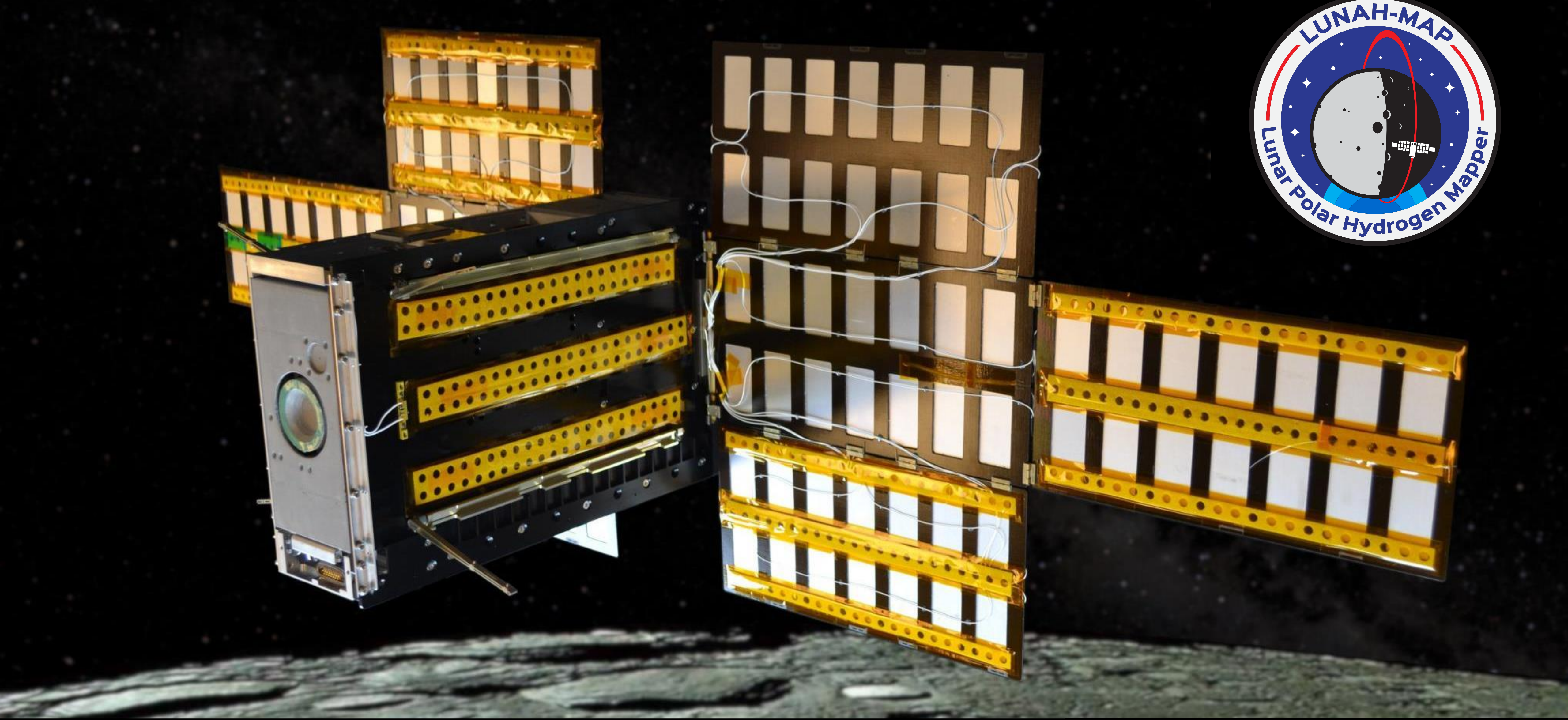


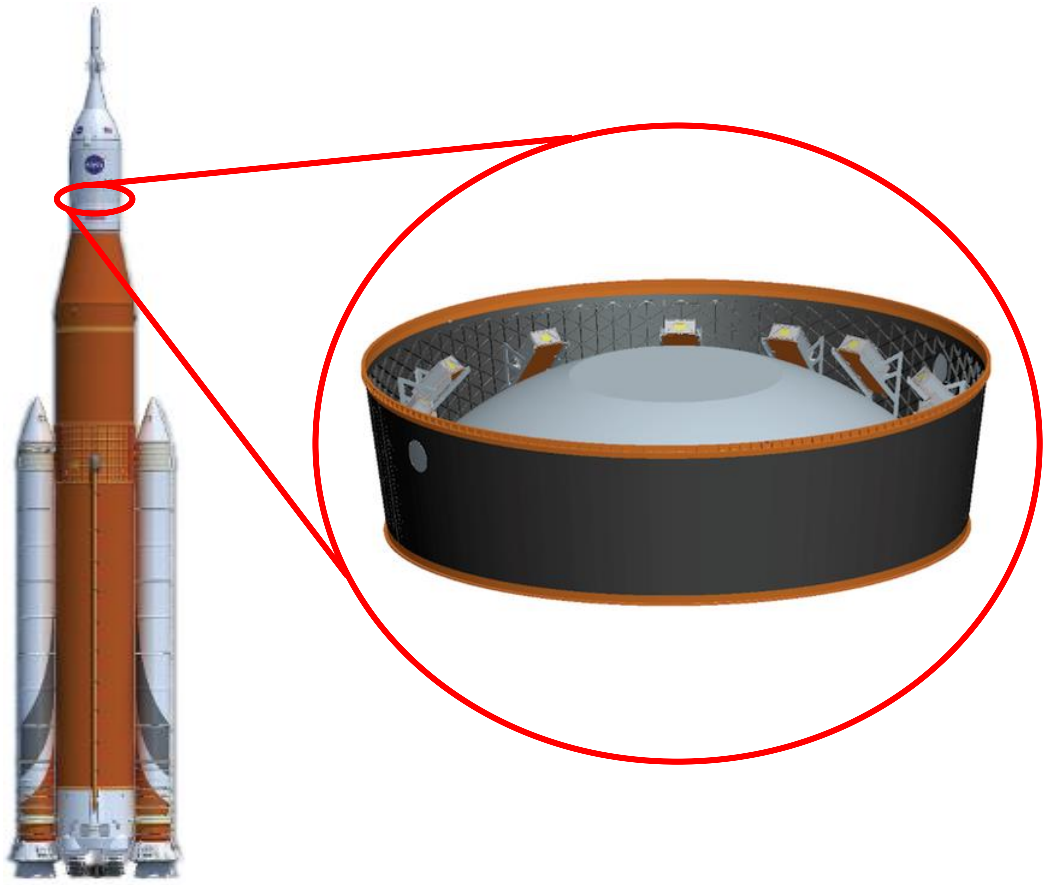
The Lunar Polar Hydrogen Mapper Mission: Low-Altitude Planetary Neutron Spectroscopy

Craig Hardgrove

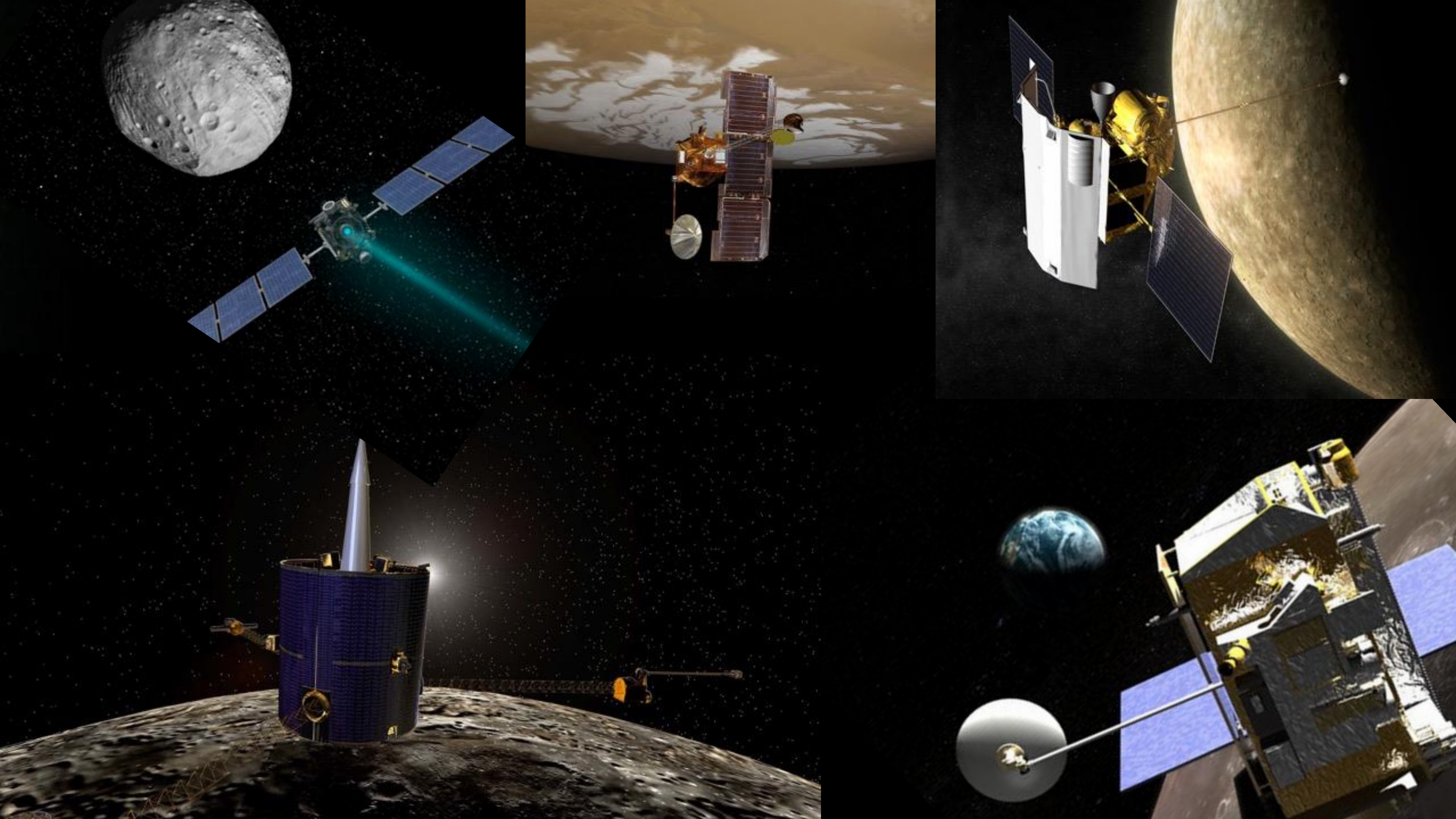
LunaH-Map Principal Investigator – Assistant Professor, School of Earth and Space Exploration, ASU

School of Earth & Space Exploration
ARIZONA STATE UNIVERSITY

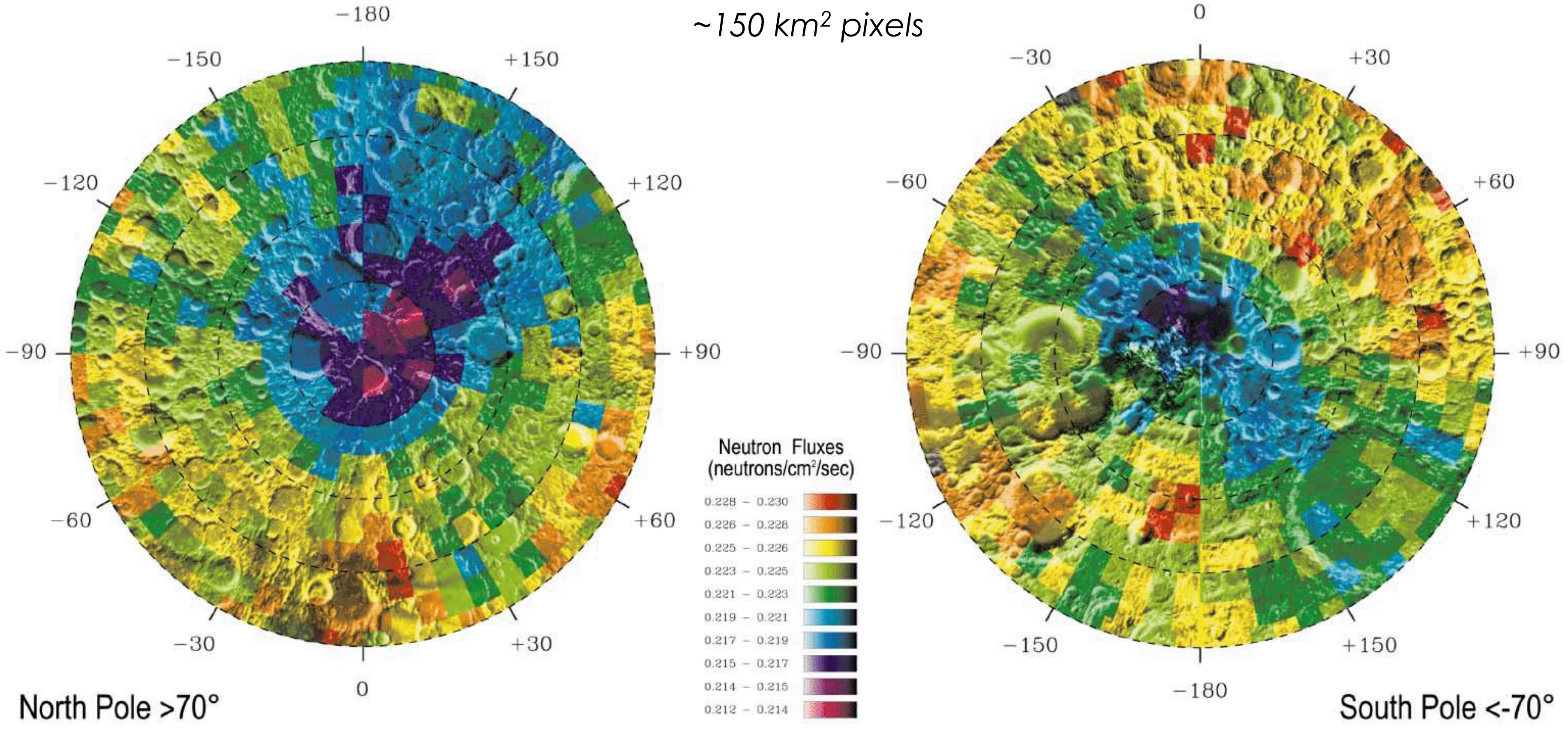
LunaH-Map Mission Overview



- 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 km^2
- **Tech Objectives**: Deep space navigation and operations using ion propulsion on a small sat



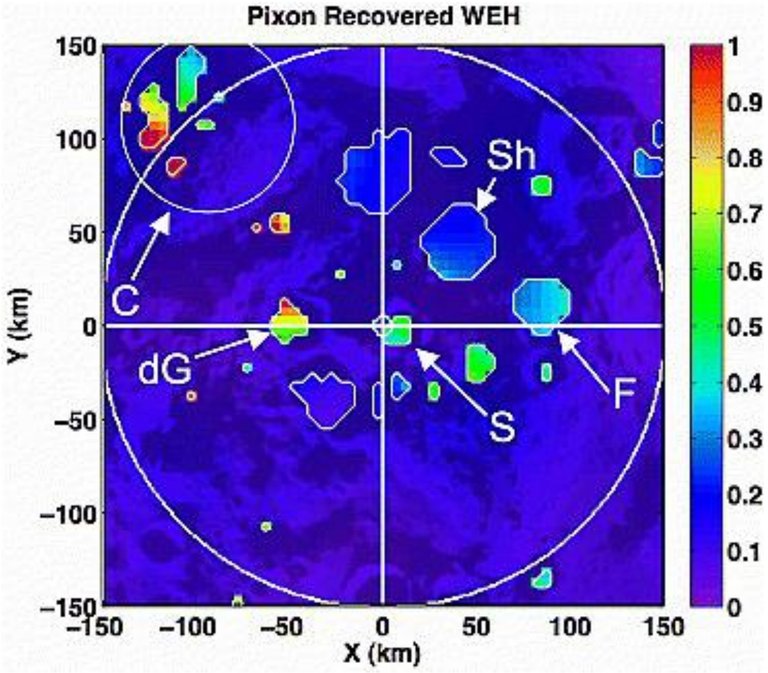
Hydrogen Distributions from Neutron Spectroscopy



*Feldman et al., Science, 281, 1496, 1998

- 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].

Bulk Lunar Hydrogen at Smaller Spatial Scales



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%)

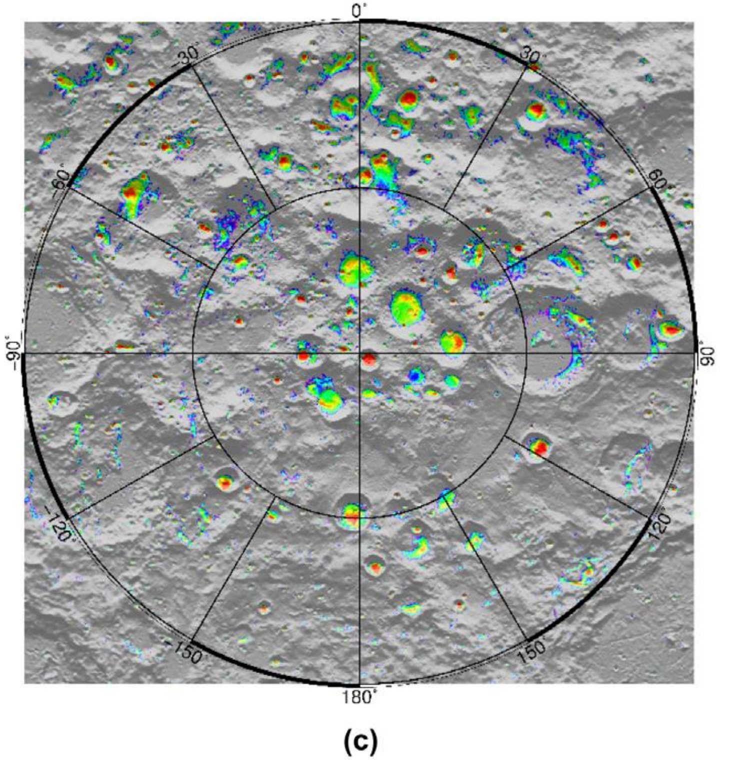
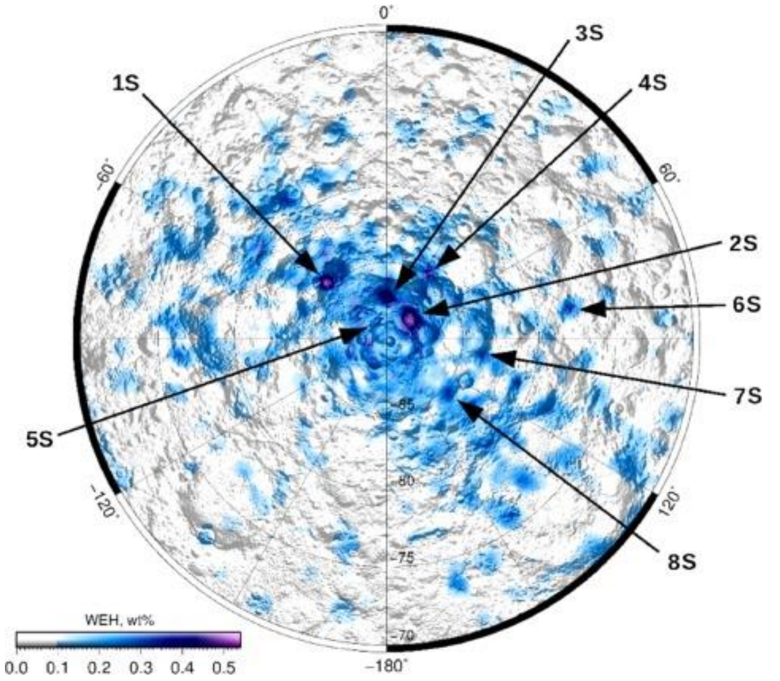
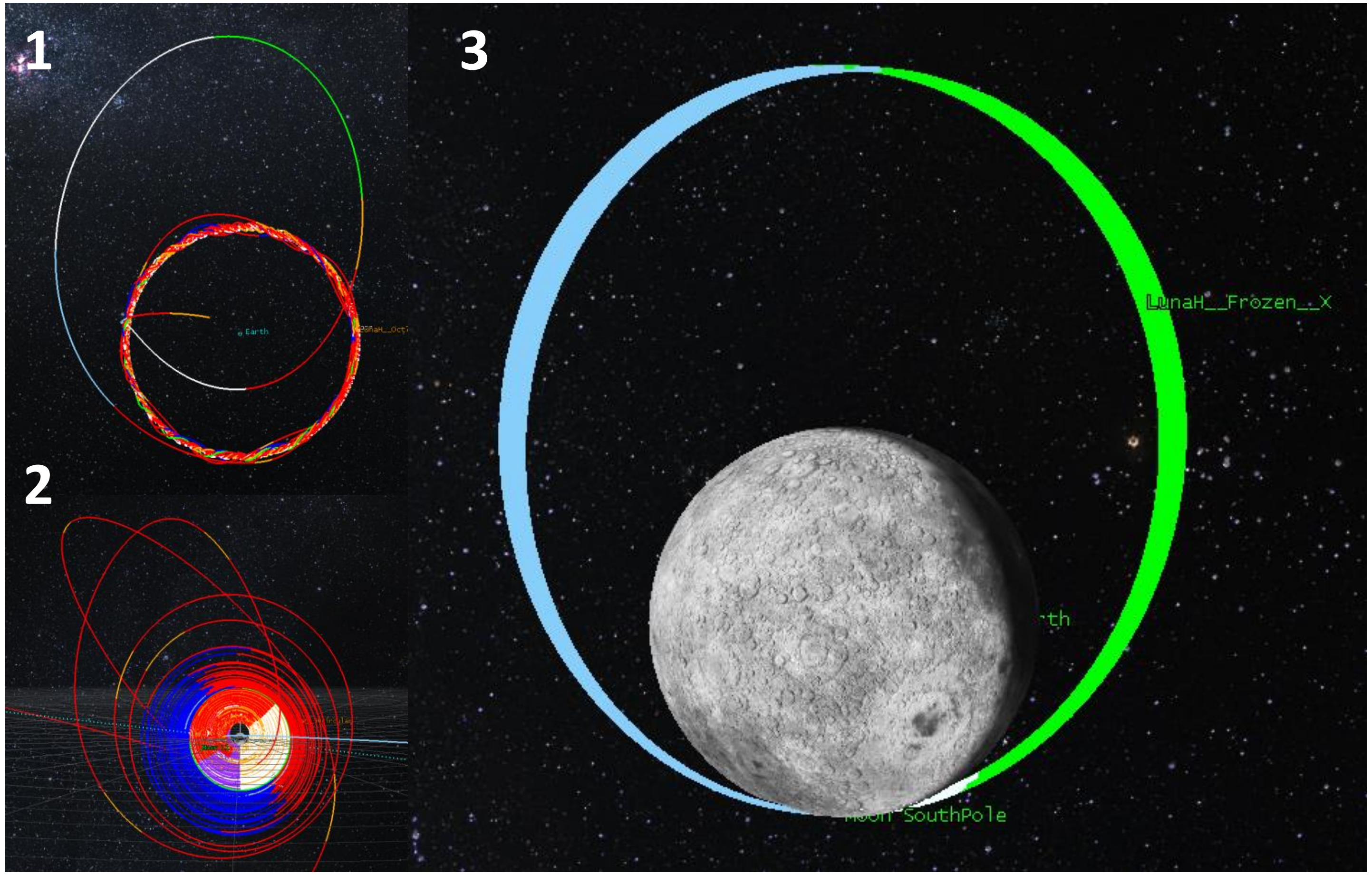


Figure 1 Map of current day ice stability depth from Siegler et al [2015] as used in constraint map development



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

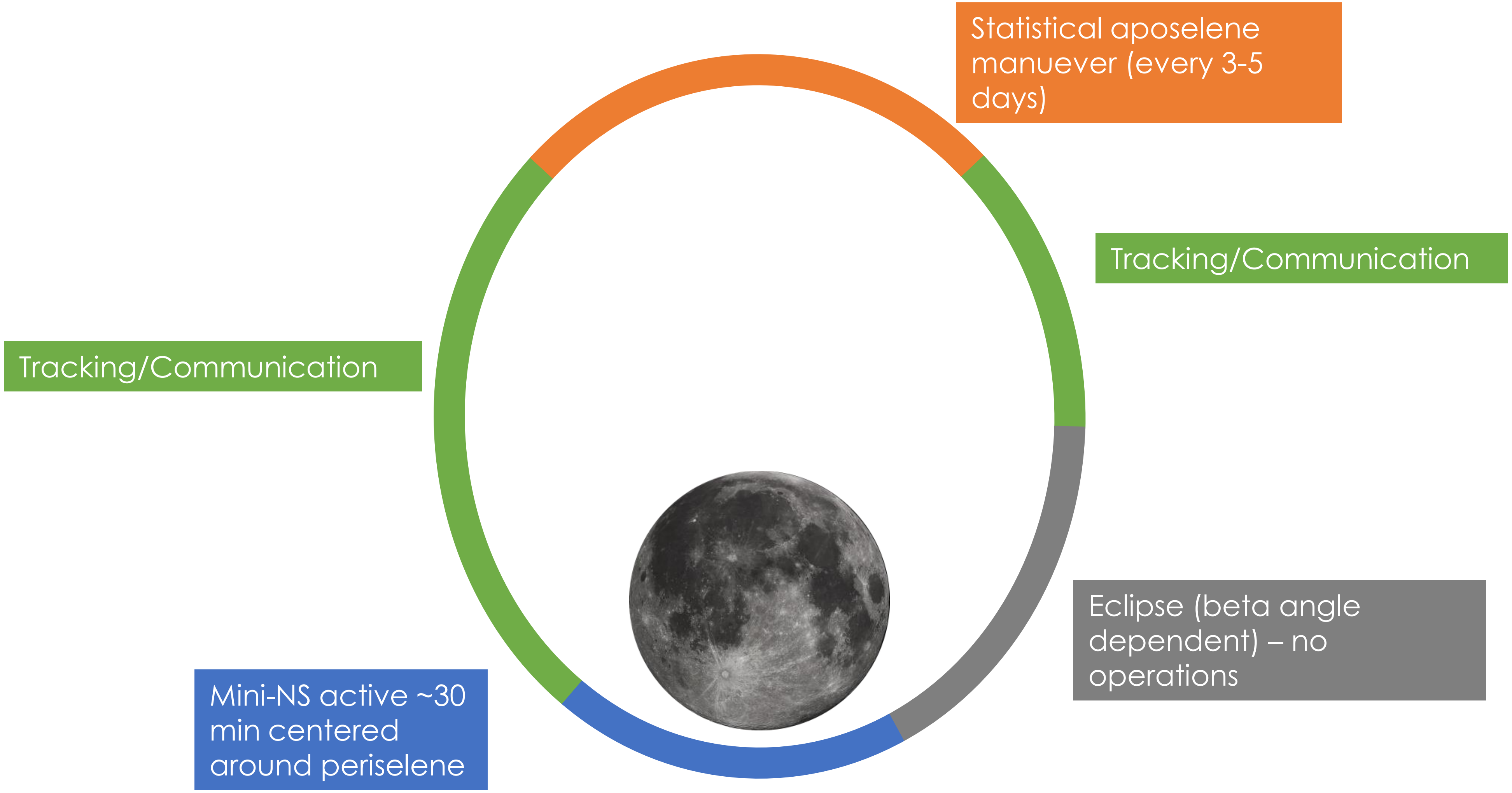
Trajectory Design



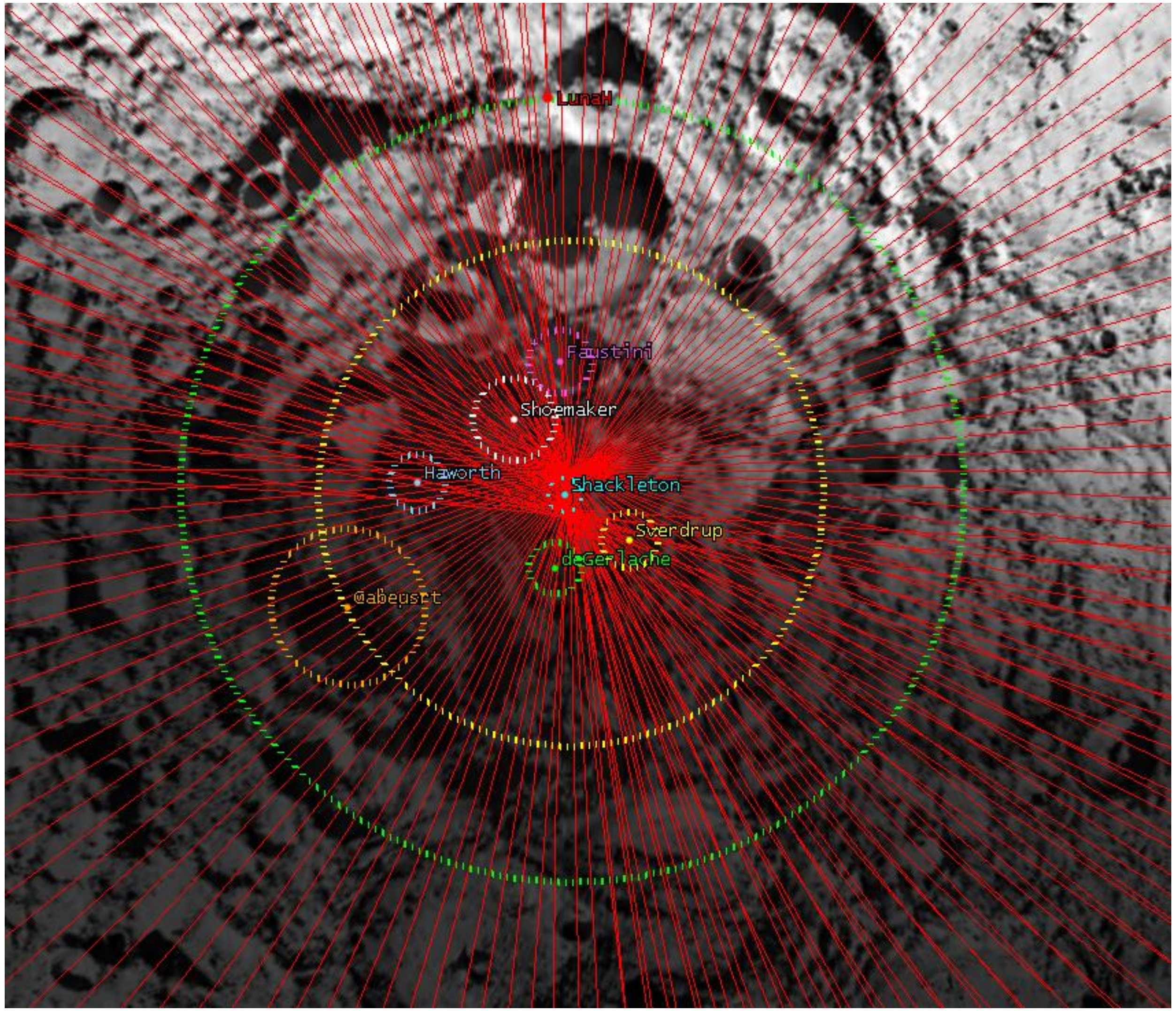
Period	4.76 hour
Aposelene Altitude	3150 km
Periselene Altitude	RAAN dependent 15-25 km
Inclination	90°
Argument of Periselene	273.5°

Genova, A. L. and Dunham, D. W. (2017) 27th AAS/AIAA Space Flight Mechanics Meeting 17-456.

Day in the Life - Science



Science Phase



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Neutron Measurements of the Moon

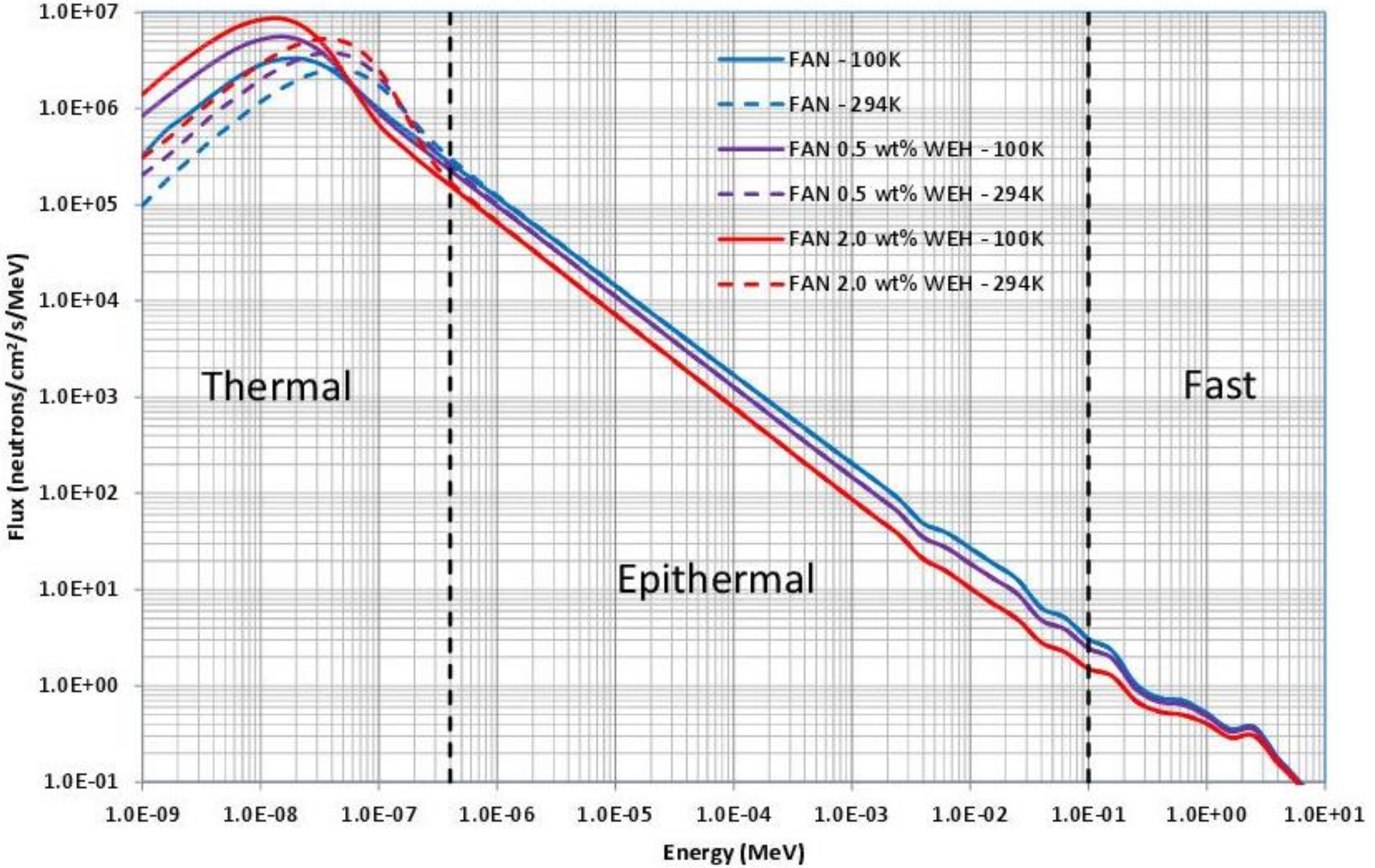
Science

- 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 cm^2)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)**

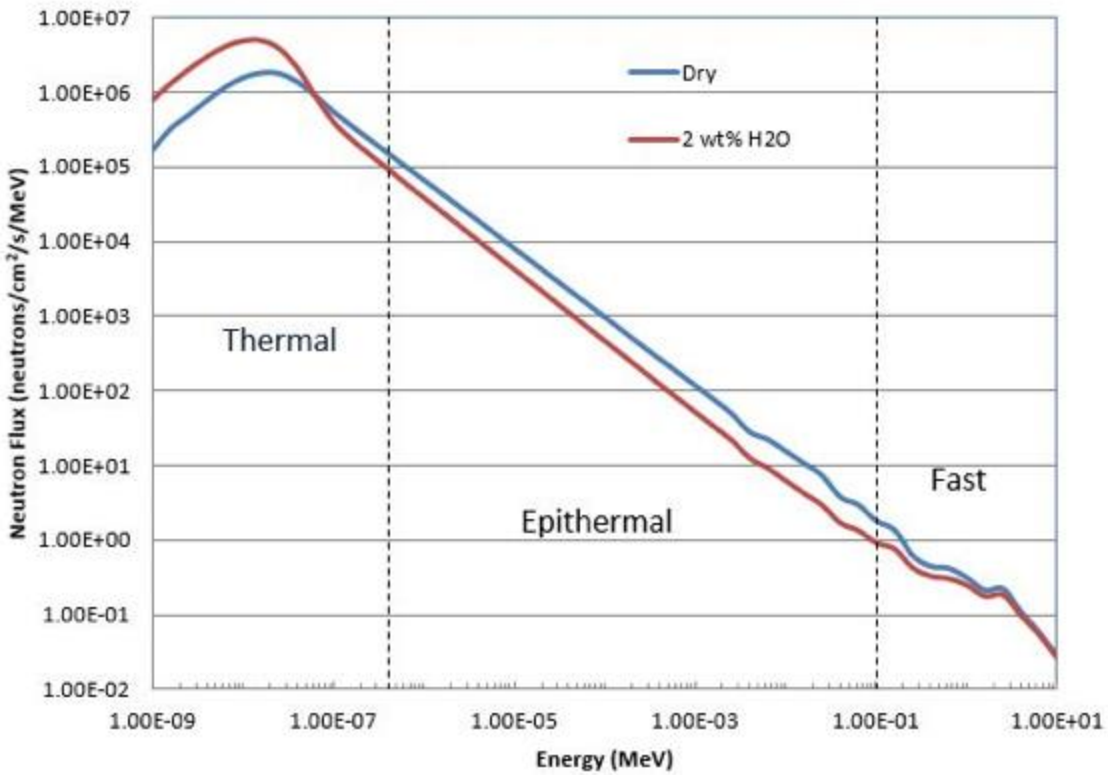
Instrument Development - FAN Neutron Energy Spectrum

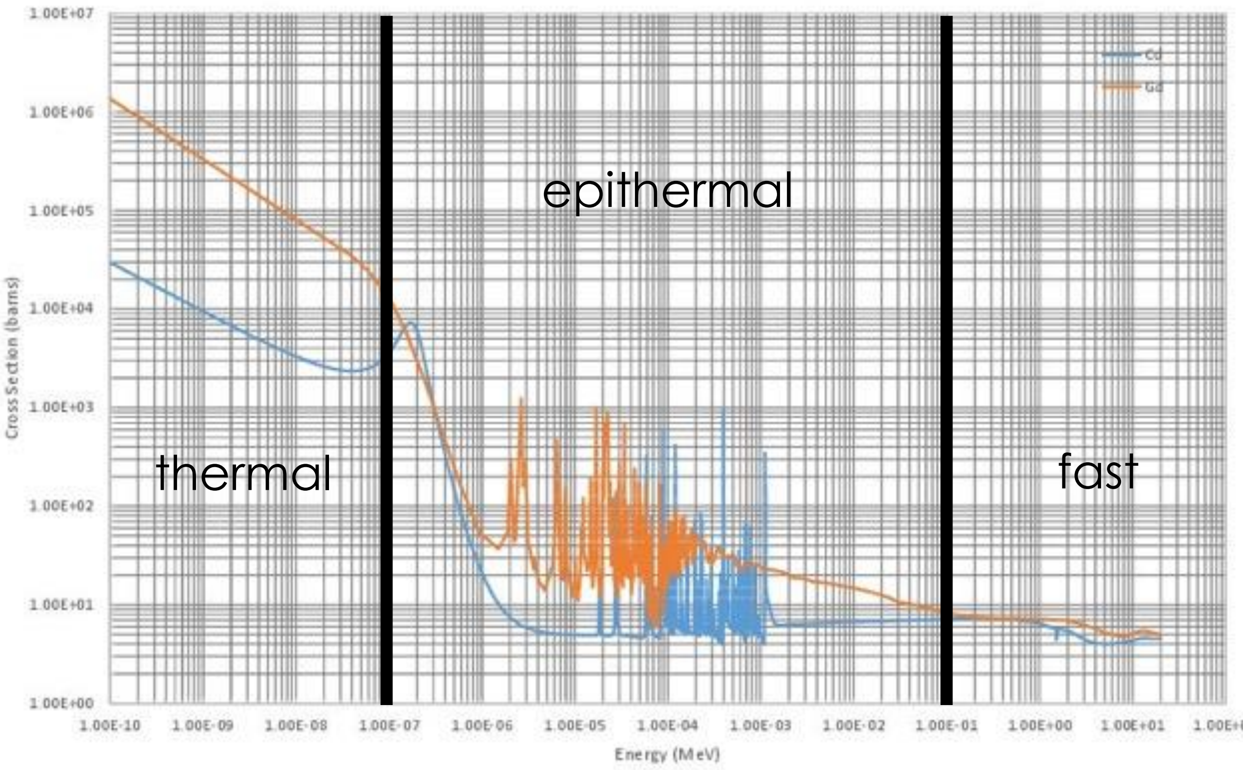


Increased hydrogen suppresses epithermal neutrons (E > 0.4 eV) and increases thermal neutrons (E < 0.4 eV)

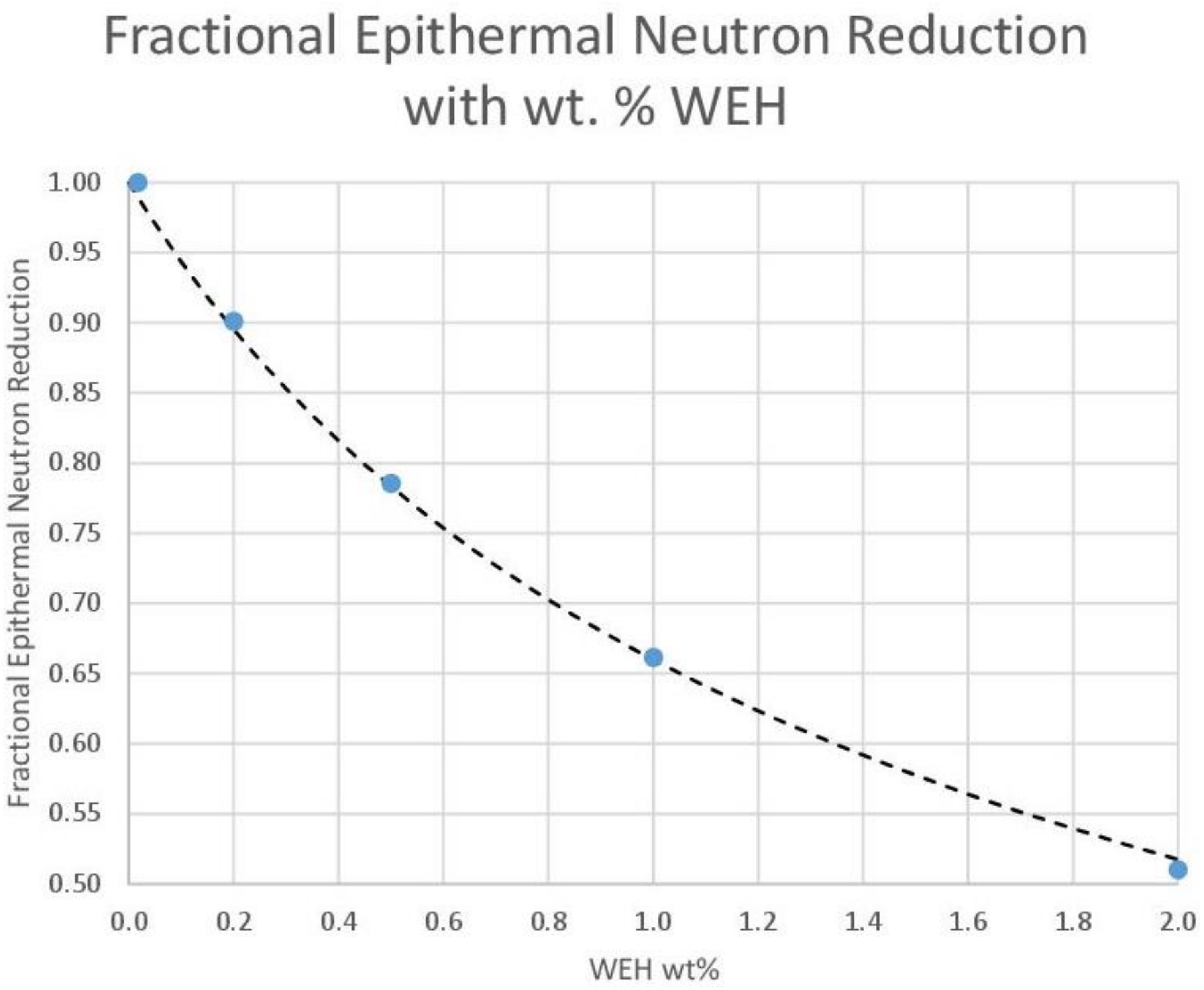
LunaH-Map's *signal* is the difference between **dry** epithermal count rate and **enriched** epithermal count rate

Neutron Detector Shielding





Neutron Absorption Cross Sections for Cd (blue line) and Gd (orange line)



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

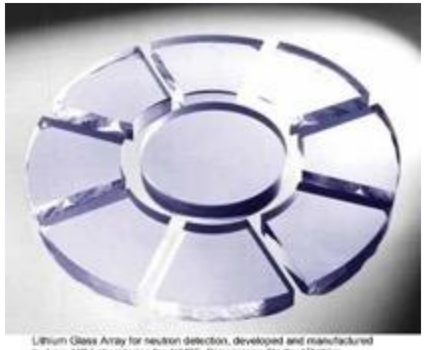
Neutron Sensitive Materials

- 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

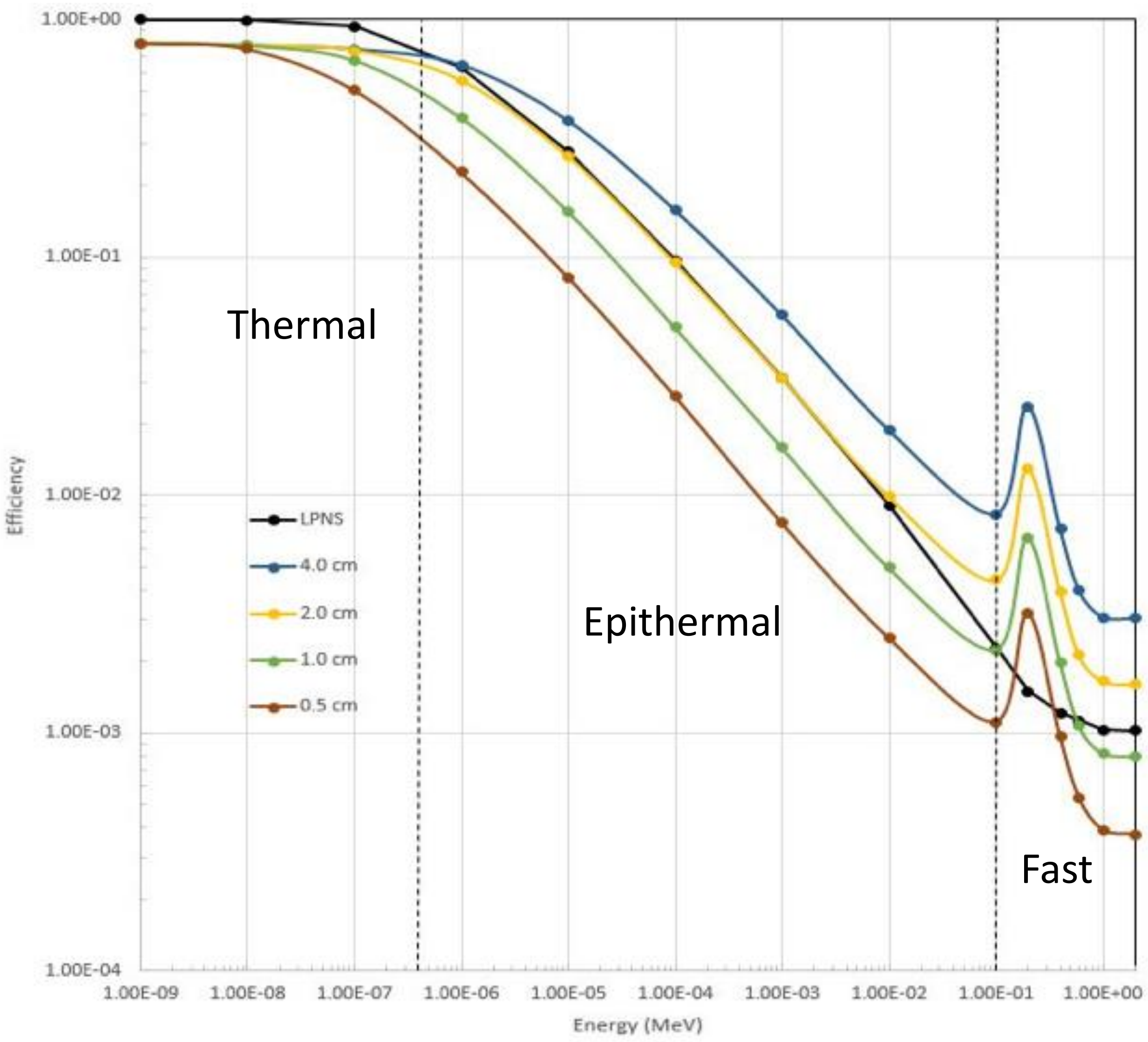


Lithium Glass Array for neutron detection, developed and manufactured by Levy Hill Laboratories for AWRE. Dimensions 8½ "by ½" thick.

Boron-Loaded Plastic

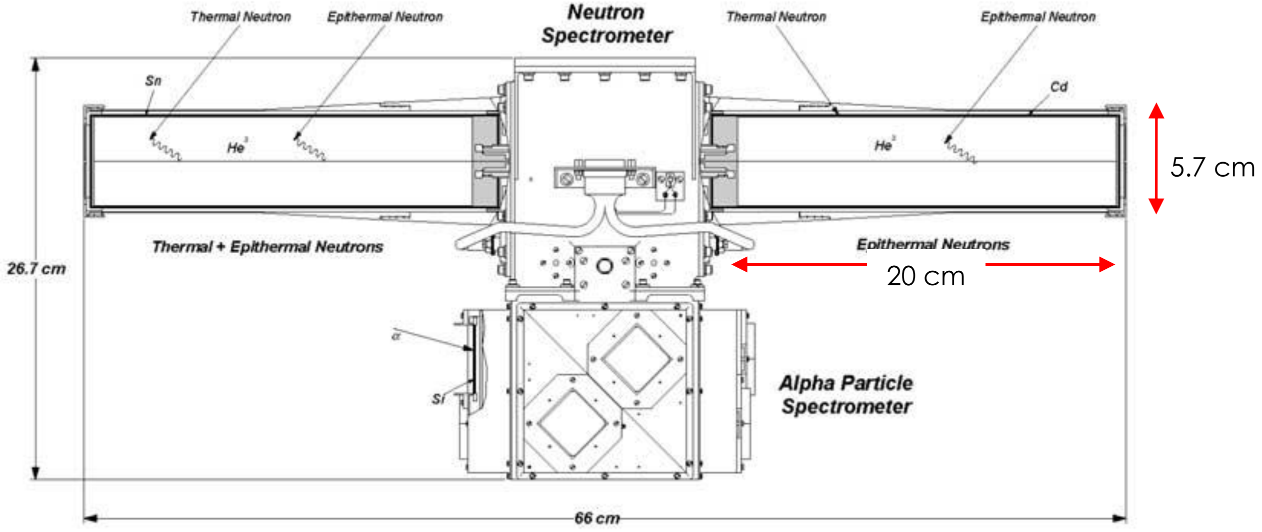
Detection Efficiency

Efficiency of 2-cm thick CLYC matches LPNS 5.7-cm diameter He-3 counter.



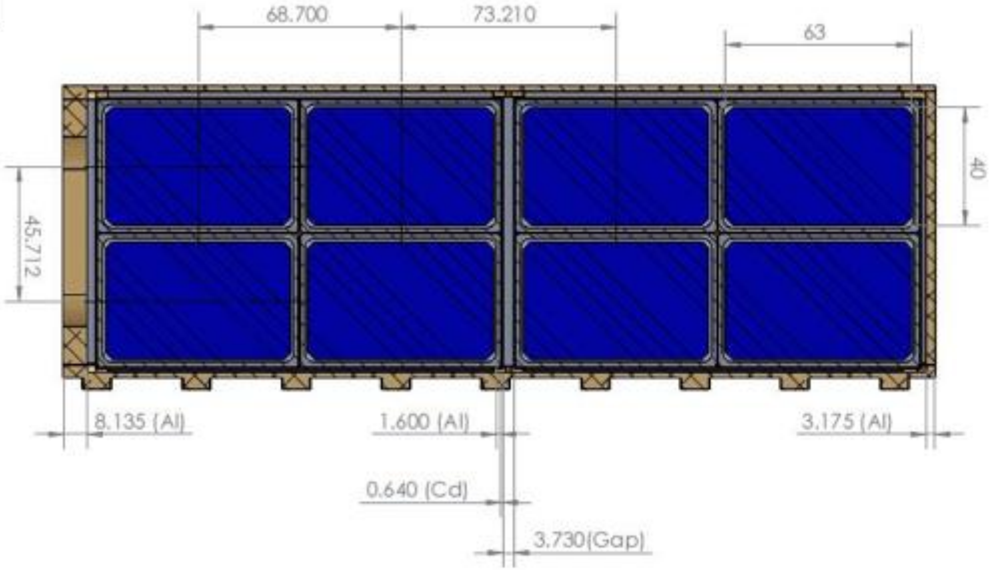
Detection Area

LPNS



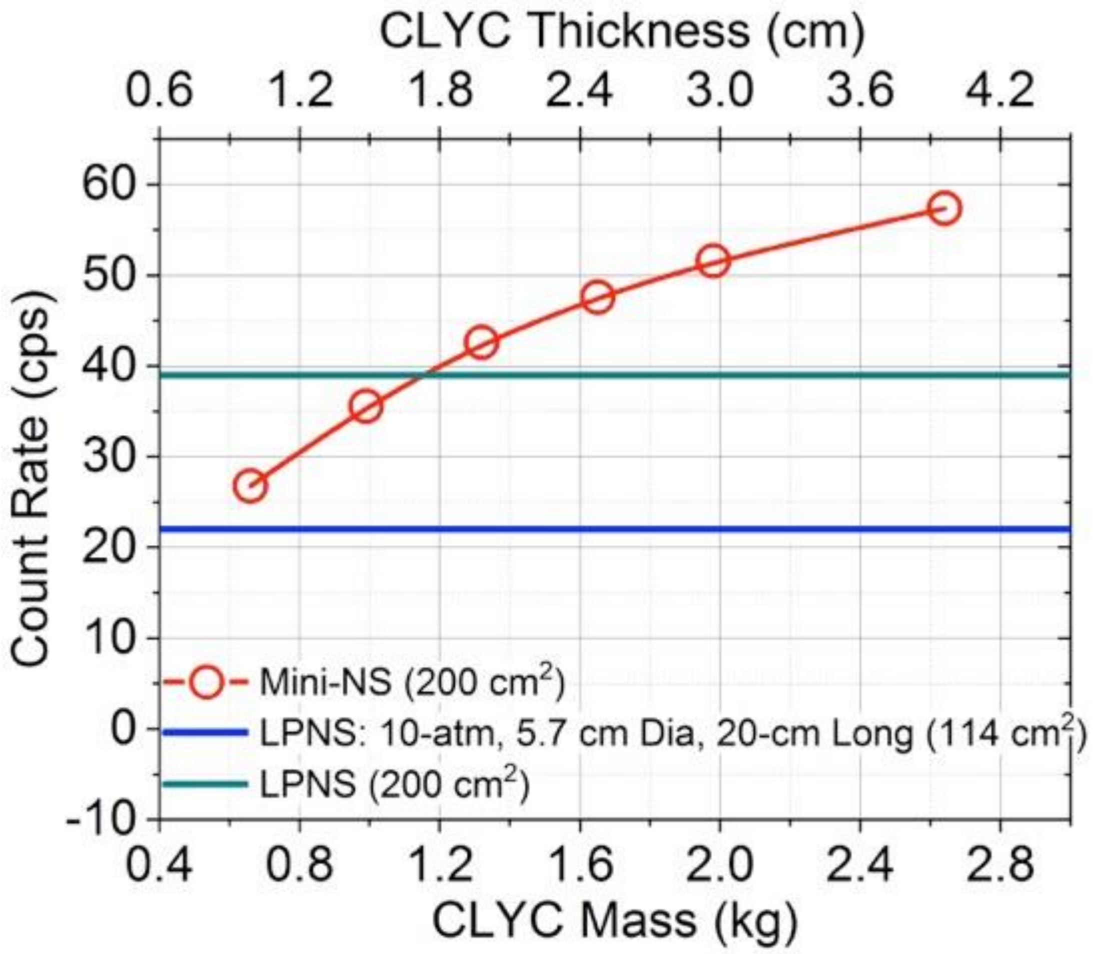
- Effective area of one LPNS He-3 tube is ~100 cm^2.
- He-3 tube gas pressure 10 atm, ~0.0014 g/cm^3
- Epithermal count rate ~20 s^{-1}.

Mini-NS



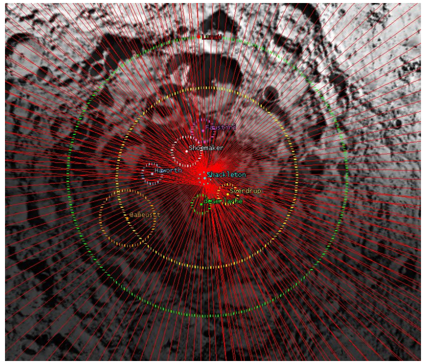
- Total area of eight Mini-NS CLYC modules is ~200 cm^2.
- CLYC density ~3.3 g/cm^3
- Epithermal count rate ~40 s^{-1}.

Modeling of Expected Count Rates

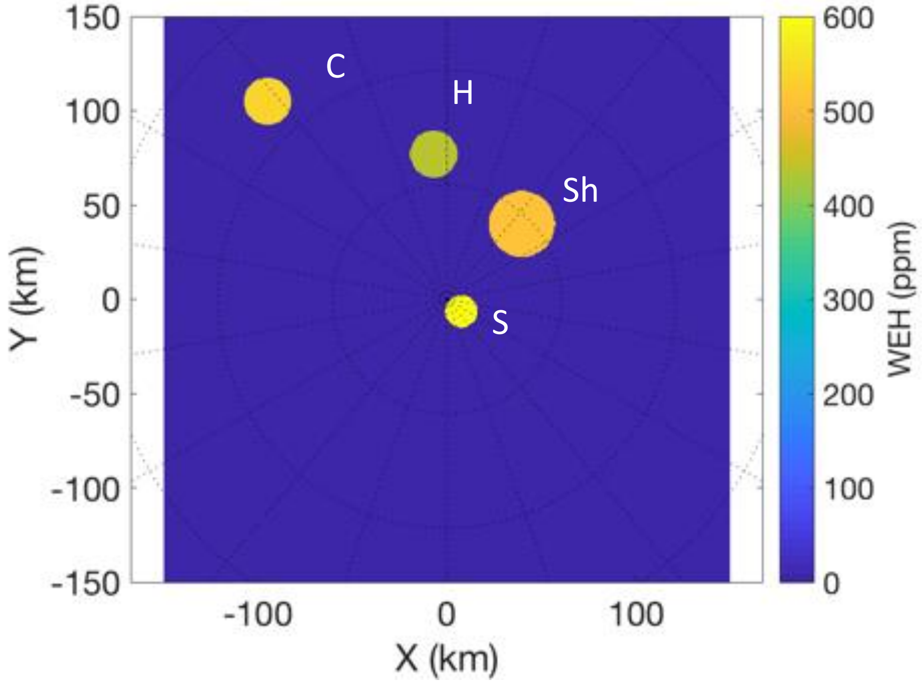


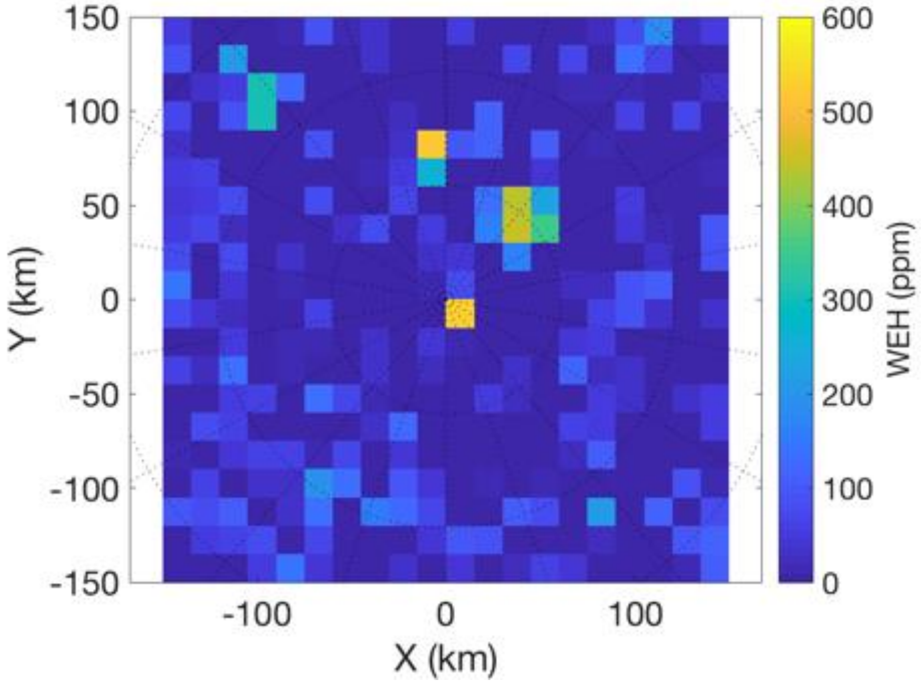
- Using lunar neutron input spectrum from 10 km altitude

South Polar Volatile Mapping



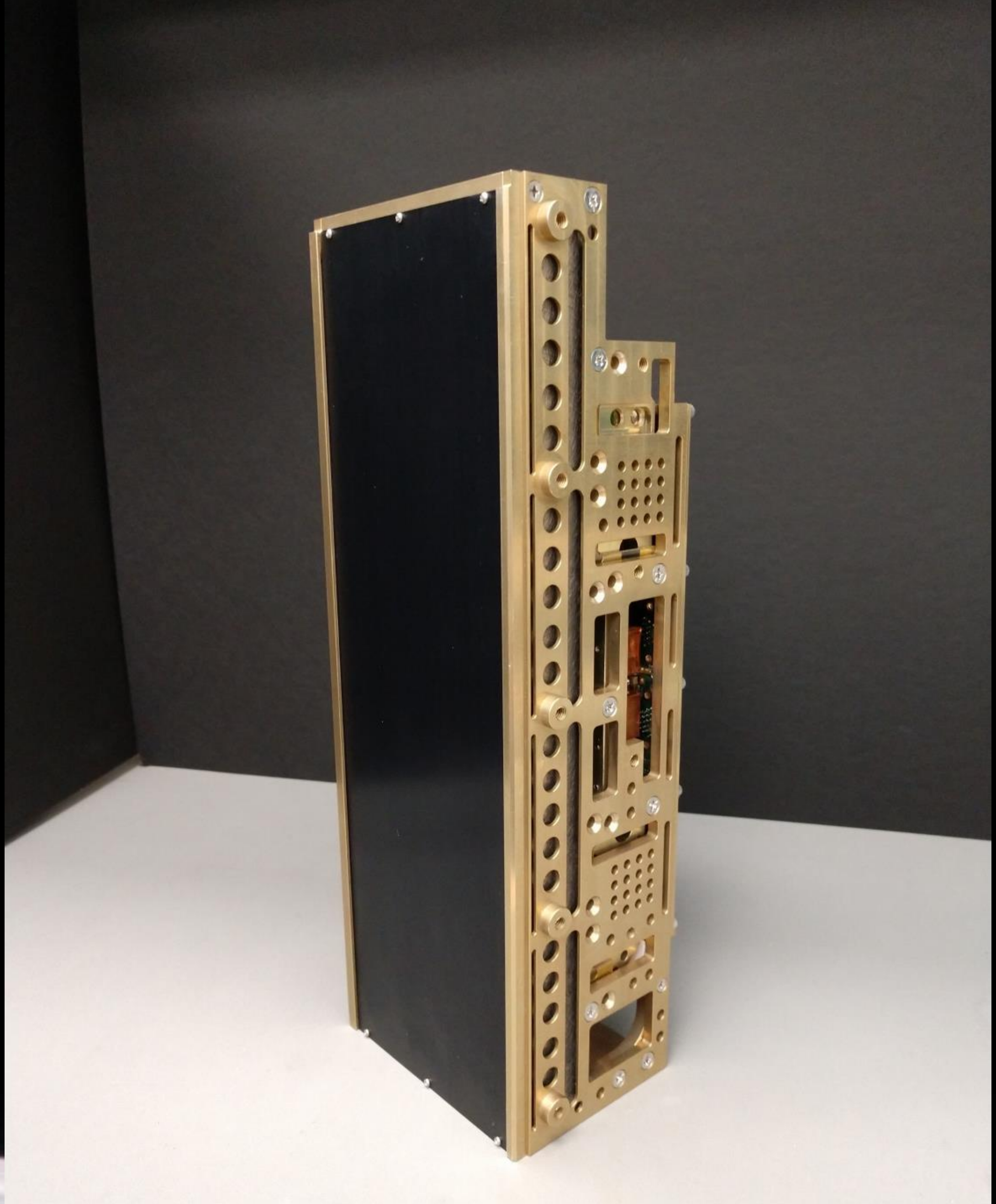
LunaH-Map 2 month science phase ground tracks



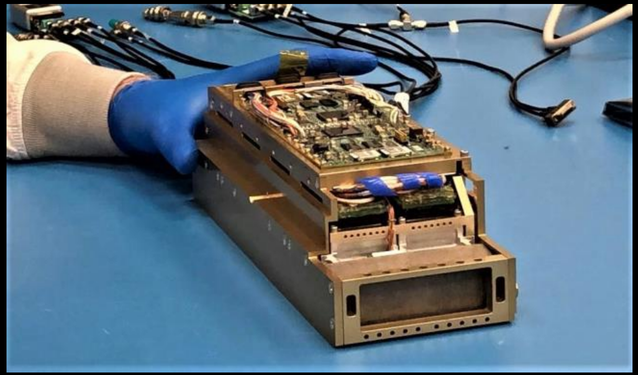


Simulation maps made from 15 x 3150 km science orbit. Basemap combines LEND high H regions (Sanin et al., 2017) and the Shackleton enrichment from pixon-reconstructed LPNS data (Elphic et al, 2007) to illustrate the type of map LunaH-Map will be able to create (West et al., LPSC 2017).

LUNAH-MAP
Lunar Polar Hydrogen Mapper



Mini-NS Flight Unit



Mini-NS: Miniature Neutron Spectrometer

School of Earth & Space Exploration
Arizona State University

RMD
A Dynasil Company

Miniature Neutron Spectrometer for CubeSats and SmallSats – Flight Unit

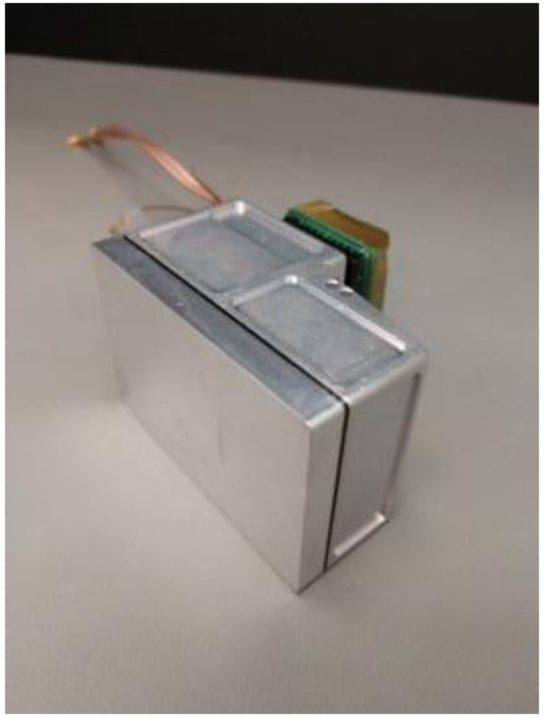
Detector	2x4 array of CLYC (elpasolite scintillator, Cs_2LiYCl_6:Ce) crystals, each crystal 4 cm x 6.3 cm x 2 cm
Dimensions	25 cm x 10 cm x 8 cm
Mass	3.3 kg
Power	10W
Data Acquisition	Counts binned every 1 sec

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

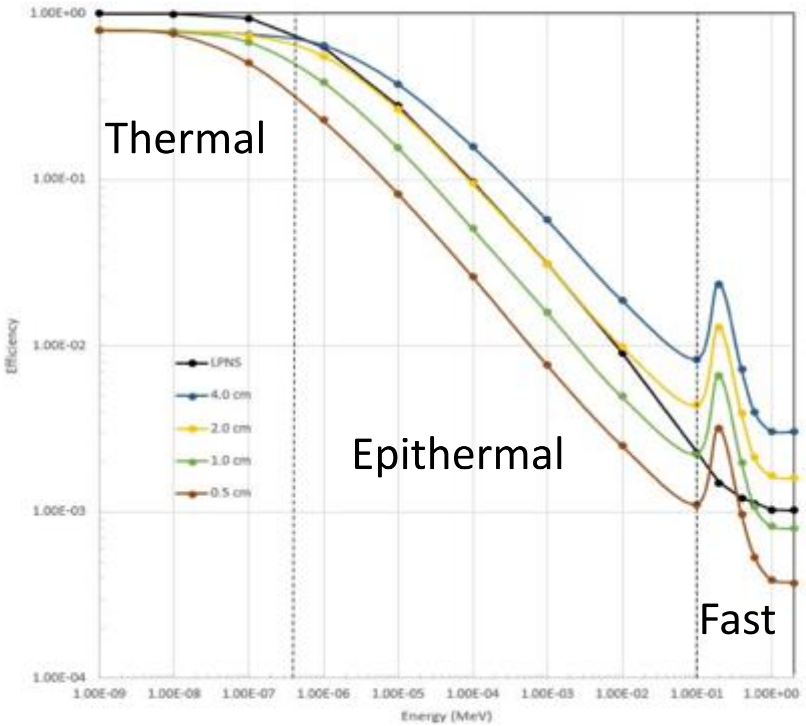
Miniature Neutron Spectrometer for CubeSats and SmallSats

Instrument Housing and Electronics

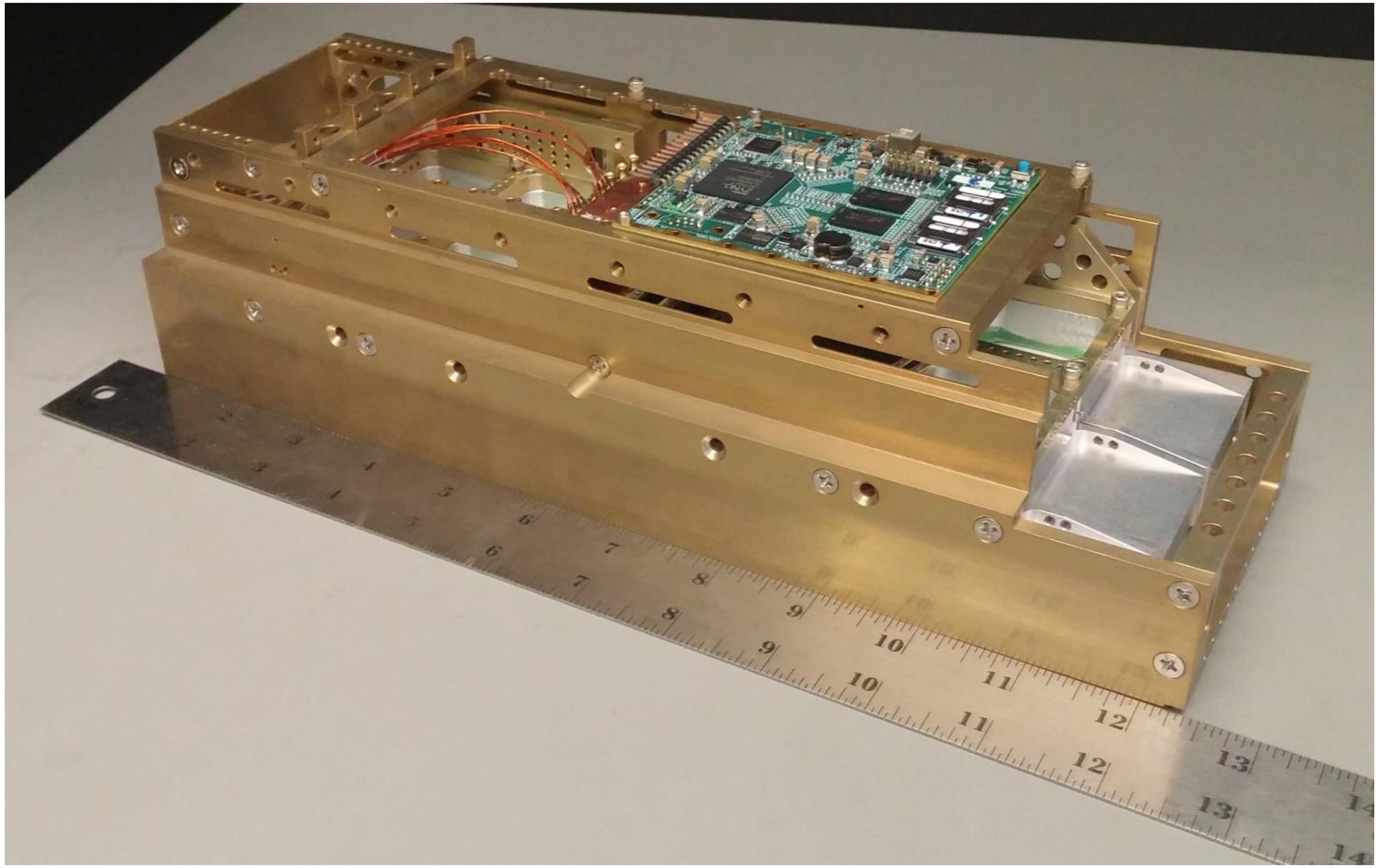
CLYC Module



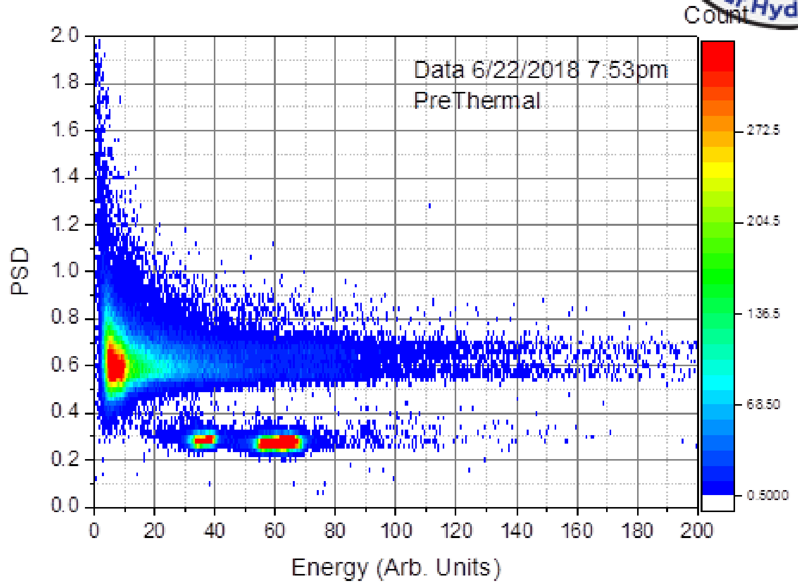
Individual CLYC module, PMT and housing (x8)



LUNAH-MAP
Lunar Polar Hydrogen Mapper



LunaH-Map protoflight Miniature Neutron Spectrometer (Mini-NS) unit with a subset of the 8 detector modules, analog and digital boards populated prior to final assembly and qualification.



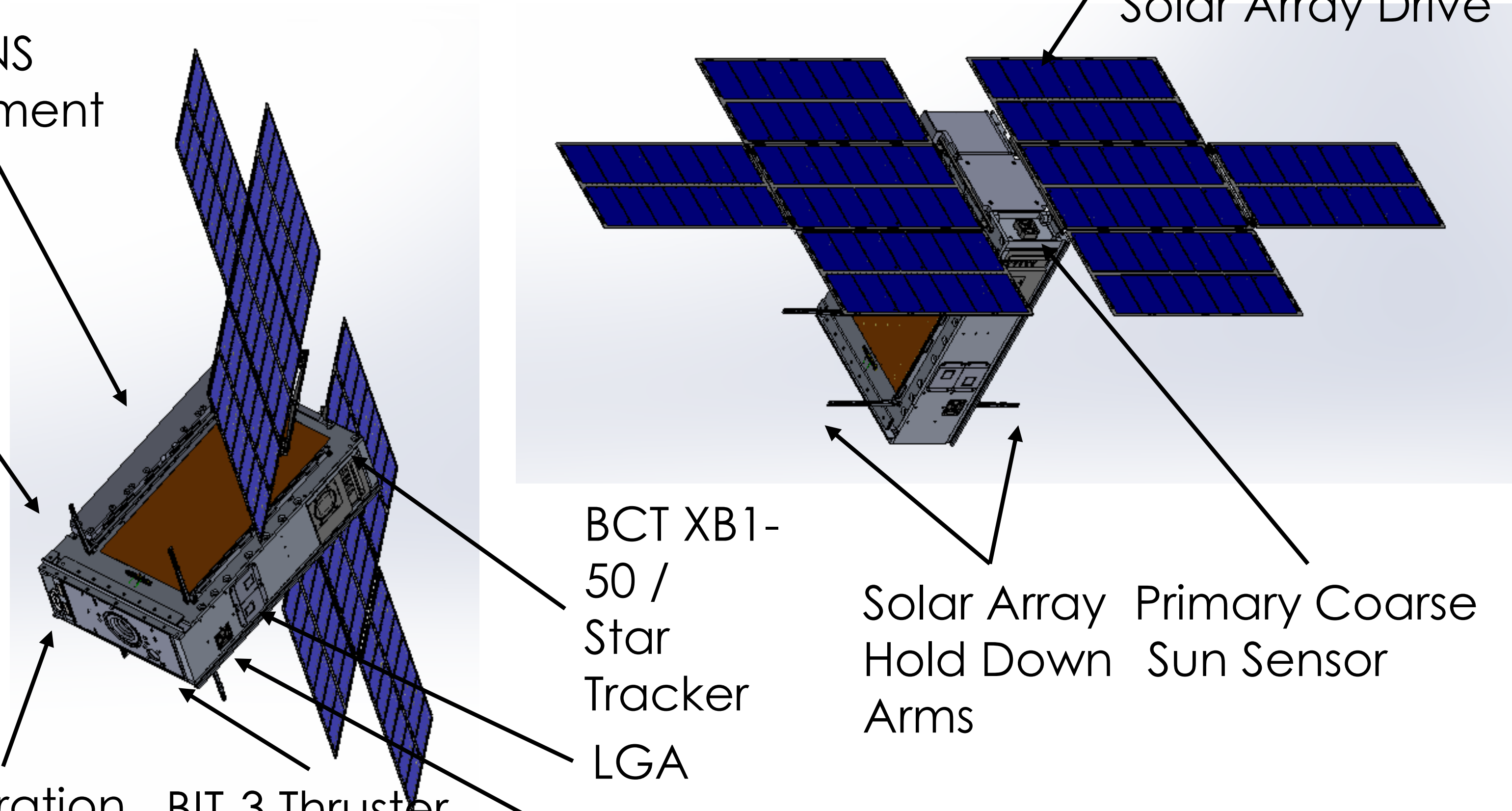
- Each Mini-NS detector module (CLYC) is sensitive to both neutrons and characteristic gamma-rays
- Neutrons and gamma-rays can be separated using pulse discrimination in the detector electronics

LUNAH-MAP
Lunar Polar Hydrogen Mapper

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)

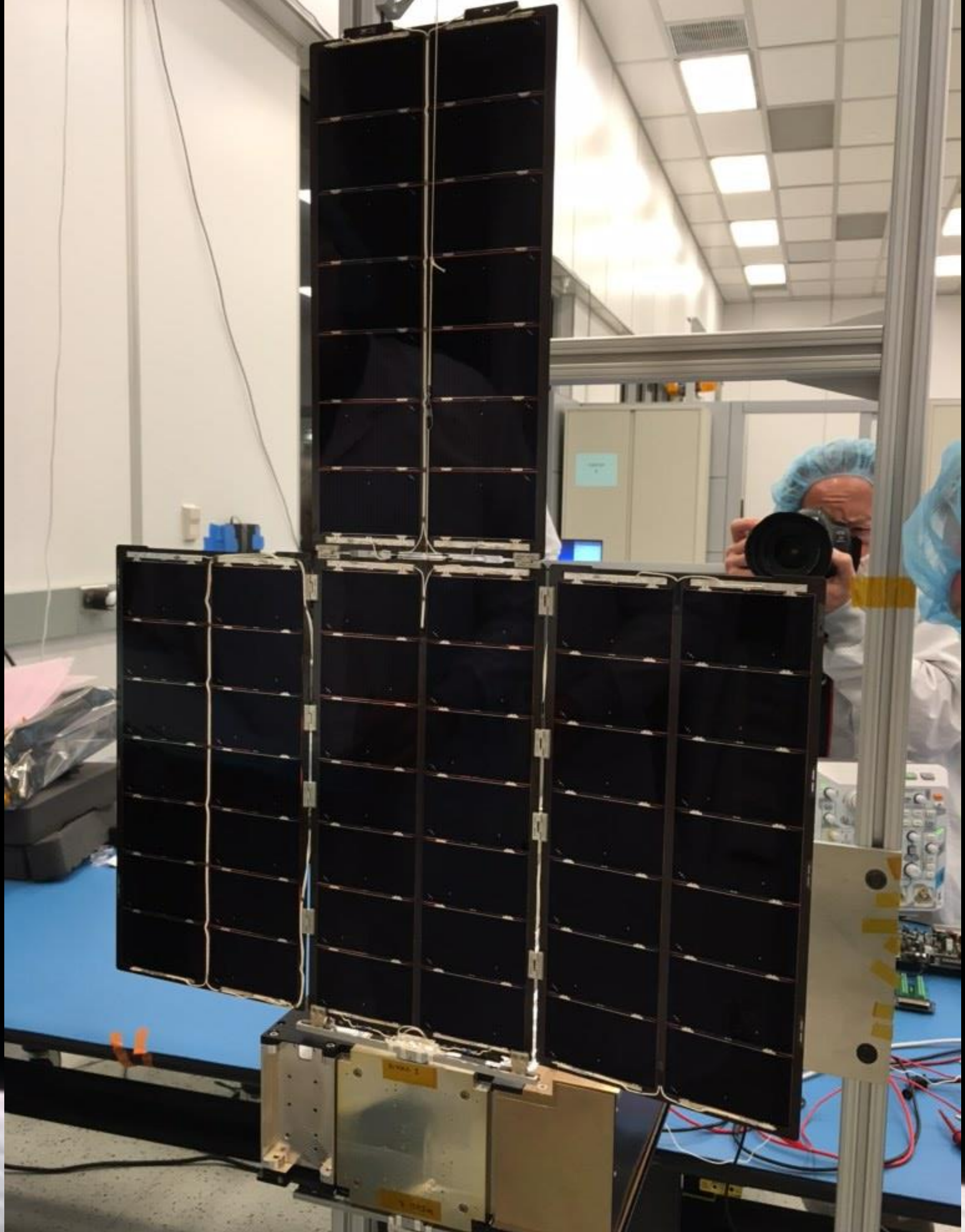
LunaH-Map Spacecraft



Spacecraft Specs

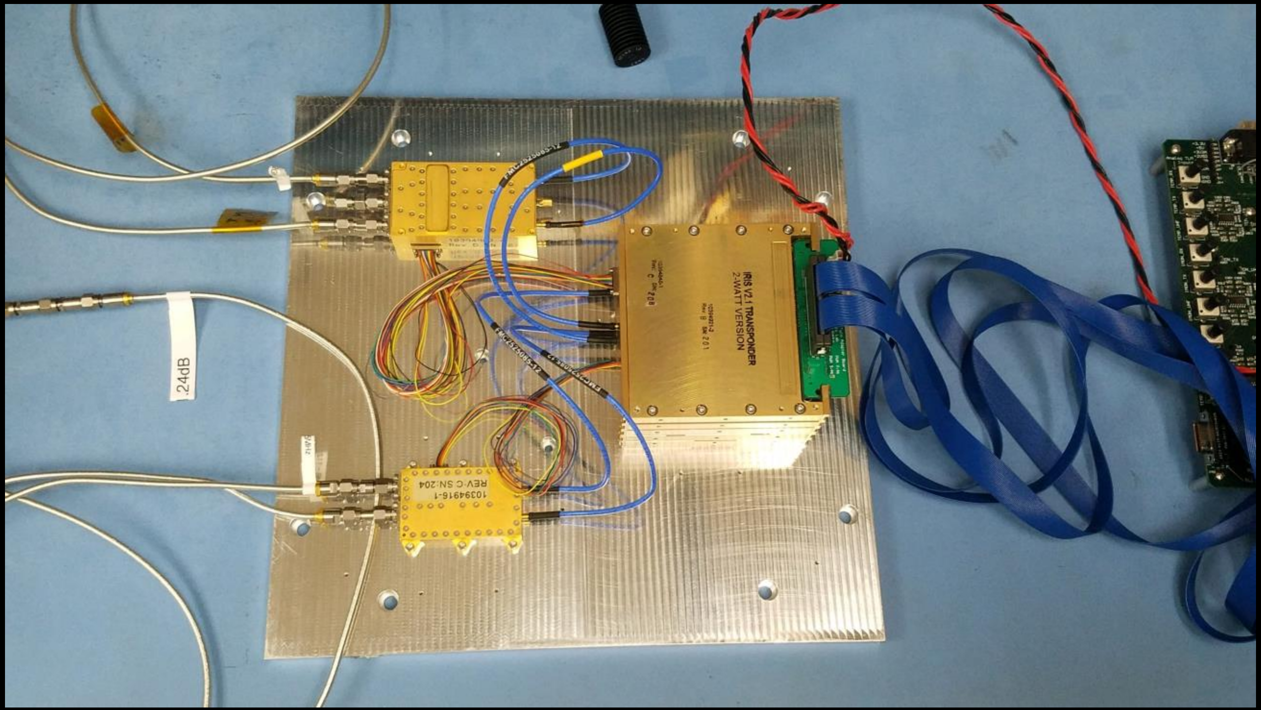
Dimensions: (stowed)	10x20x30cm
Mass	14 kg
Power	90W BOL 56W-hr Battery
Propulsion	Busek BIT-3 Ion Thruster
Comm.	JPL Iris Deep Space Transponder
C&DH / GN&C	BCT XB1-50

School of Earth and Space Exploration
Arizona State University



LunaH-Map MMA eHawk+ Flight Solar Arrays – Delivered February 2019

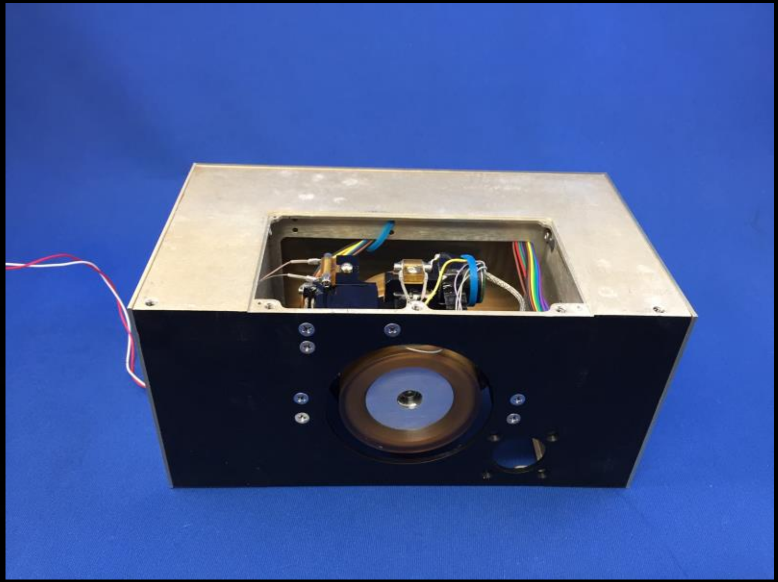
LUNAH-MAP
Lunar Polar Hydrogen Mapper



LunaH-Map Flight Iris radio – Delivered February 2019

Jet Propulsion Laboratory
California Institute of Technology

LUNAH-MAP
Lunar Polar Hydrogen Mapper



LunaH-Map Flight BIT-3

BIT-3 QM Hot Fire Iodine Testing

BUSEK
pace Propulsion
and Systems

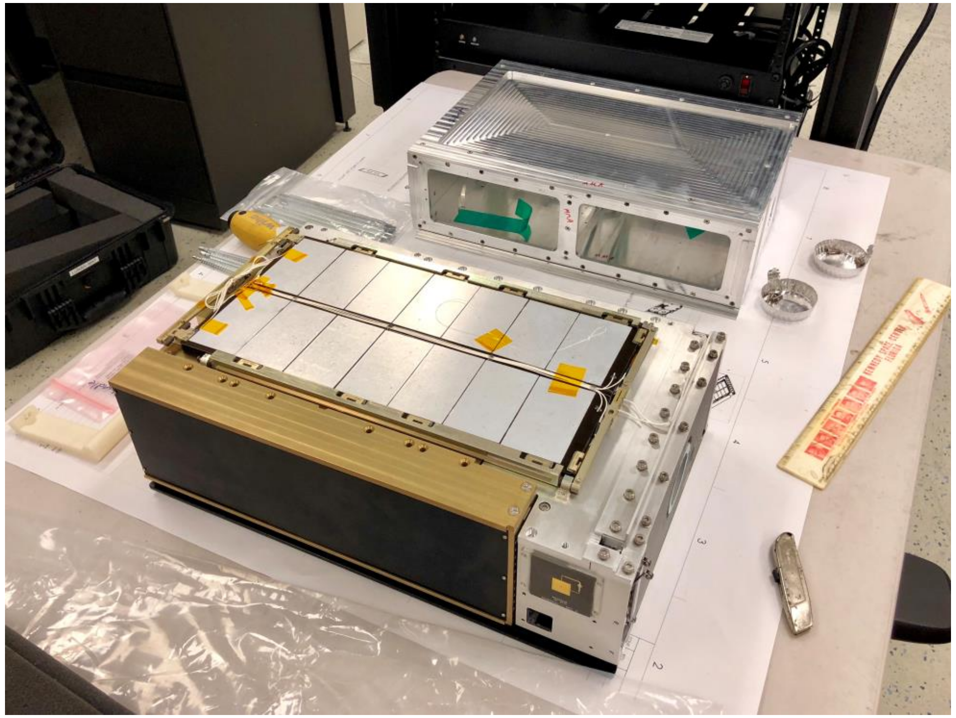
LUNAH-MAP
Lunar Polar Hydrogen Mapper

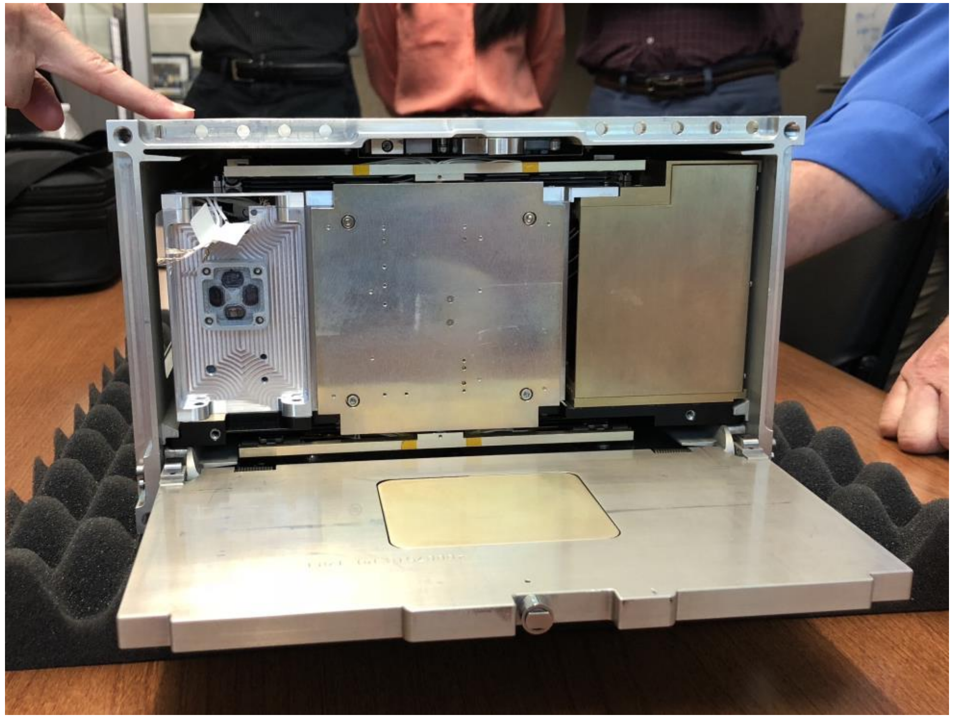
- MOC co-located in ASU's shared operations facility
- JPL AIT for spacecraft uplink and downlink
- KinetX provides mission navigation
- ASU science/instrument ops development coincident with Mars 2020 and Psyche missions

Qwaltec

KINETX AEROSPACE

LunaH-Map Spacecraft EDU





- Flight instrument chassis machined for fit checks in spacecraft EDU at ASU
- Fit check in SLS EM-1 dispenser at NASA MSFC

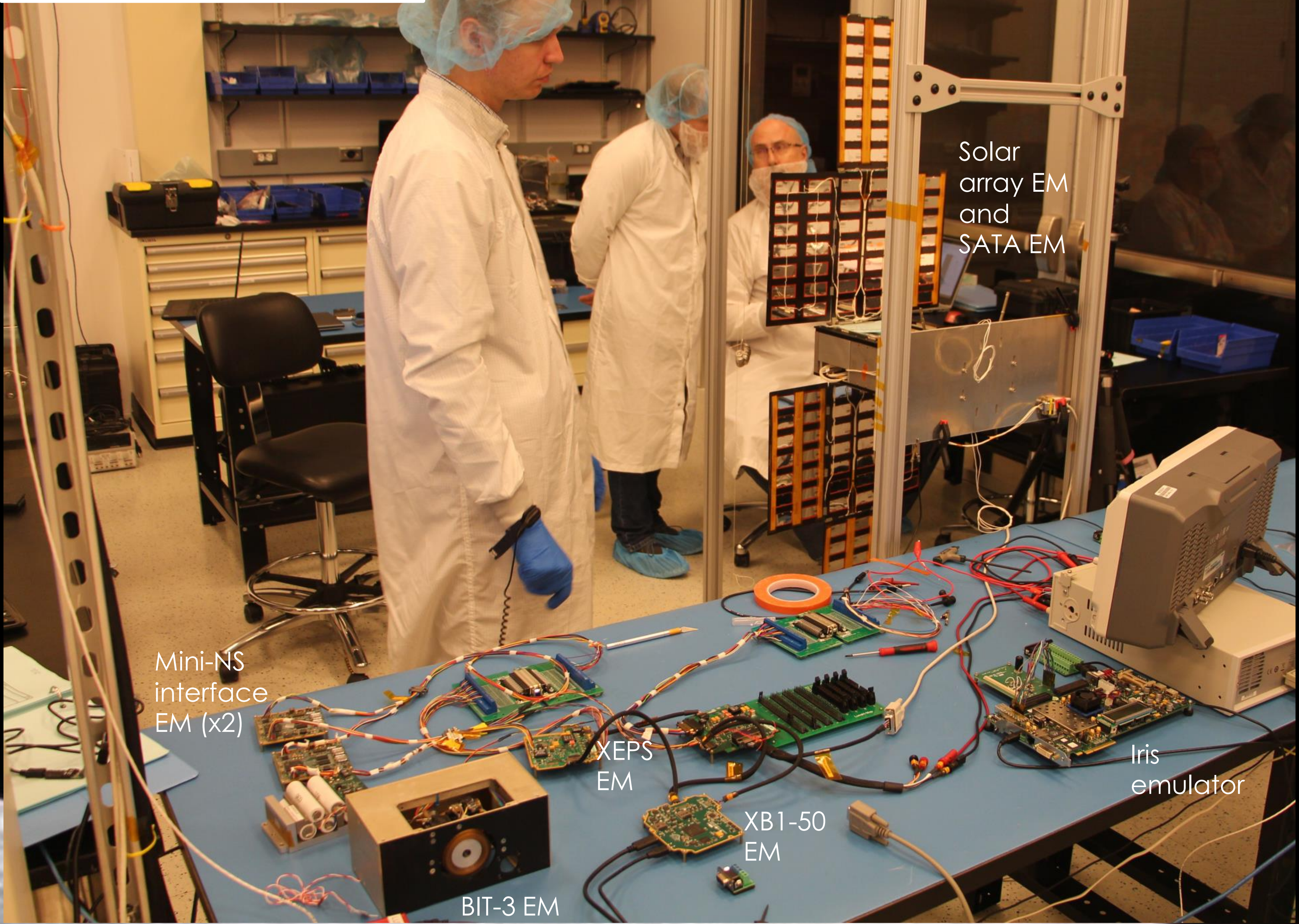
LunaH-Map Status

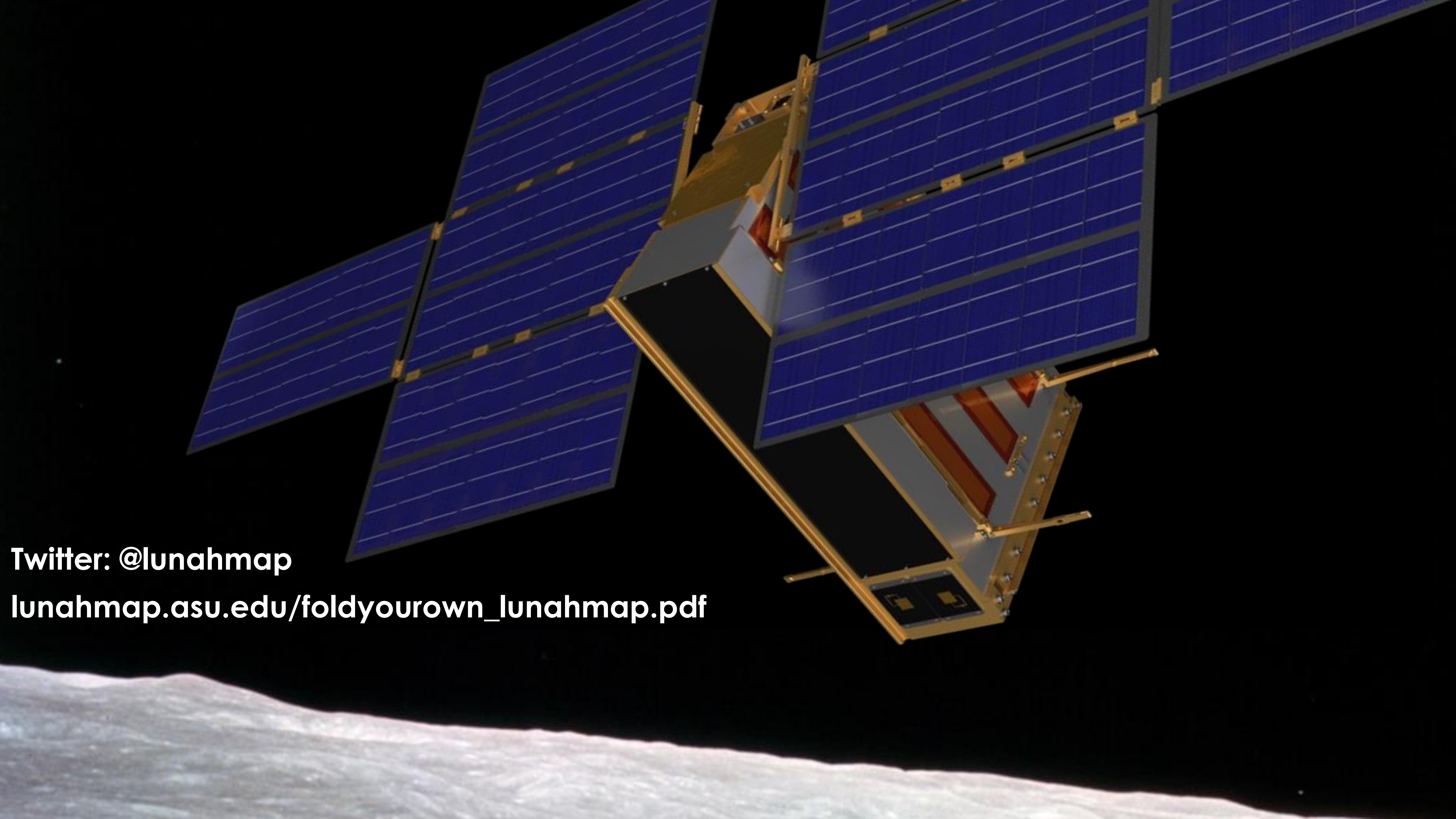
All subsystem EM units delivered and integrated into the LunaH-Map flatsat (labeled in image)

On schedule for delivery in late 2019

<u>Current Engineering Team Activities</u>

- Electrical I&T of flight units,
- EM unit testing
- Developing AIT command/telemetry tools




Twitter: @lunahmap
lunahmap.asu.edu/foldyourown_lunahmap.pdf

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 on April 30, 2019
- Flight GNC and C&DH System – scheduled on May 15, 2019
- Phase 3 Safety Review – scheduled on September 25, 2019
- Spacecraft Delivery to Tyvak – scheduled on October 30, 2019
- Launch-SLS EM-1 – scheduled on June 26, 2020

LunaH-Map Program Milestones to Date		
IAA	11 December 2015	Δ-IAA REQUIRED
Δ-IAA	24 February 2016	PASSED with RFAs
SRR	8 April 2016	PASSED with RFAs
I-PDR	9 June 2016	PASSED with RFAs
Phase 1 SR	21 June 2016	PASSED
M-PDR	25 July 2016	PASSED with RFAs
CDR	29 June 2017	COMPLETED
Phase 2 SR	9 Nov 2017	COMPLETED
Integration Workshop	7 Dec 2017	COMPLETED

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.