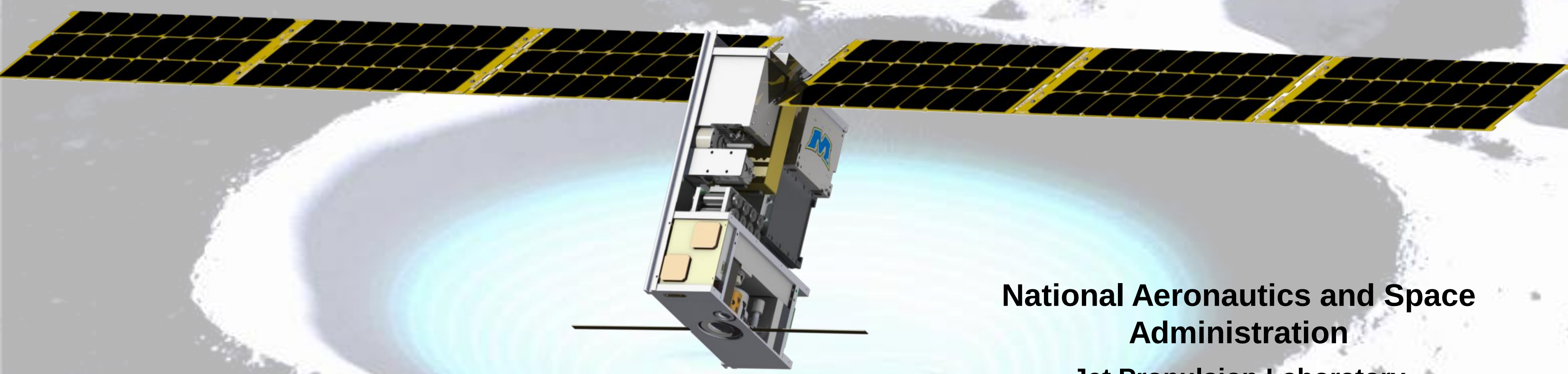
The Lunar Ice Cube Missions

P.E. Clark (CalTech/JPL),
B.Malphrus (Morehead State University),
W. Farrell, N. Petro, R. MacDowall, T. Hurford, and C. Brambora (NASA/GSFC)
and members of the Lunar ICe Cube Team



National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Government sponsorship acknowledged.

Jet Propulsion Laboratory
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Current Status

EM1 Launch now 2020.

Lunar Ice Cube, Lunar Flashlight, LunaHMap all passed CDR.

Publications (Source): Online Presentations, Short papers for all three from 2015 at LPSC, LEAG, and Interplanetary SmallSat Conference. Papers, Clark et al, 2016, SPIE Optics on Lunar Ice Cube; Vinckier et al, 2017, SPIE Optics, and Imken et al, 2017, IEEE on Lunar Flashlight.

For Lunar Ice Cube Science:

All critical / long-lead Flight hardware has been ordered.

FlatSat with non rad-hard subsystems and emulators is close to completion.

Development and testing Data System beginning this summer.

CubeSat Flight System Development for Enabling Deep Space Science

Travis Imken
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-5608
Travis.Imken@jpl.nasa.gov

Julie Castillo-Rogez
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-640-9231
Julie.C.Castillo@jpl.nasa.gov

Yutao He
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-2955
Yutao.He@jpl.nasa.gov

John Baker
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-5004

Anne Marinan
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-9281

Design and characterization of a low cost CubeSat multi-band optical receiver to map water ice on the lunar surface for the Lunar Flashlight mission

Quentin Vinckier[a], Karlton Crabtree[b], Christopher G. Paine[a], Paul O. Hayne[a], Glenn R. Sellar[a]
[a]California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA, USA 91109; [b]Photon Engineering LLC, 310 S Williams Blvd #222, Tucson, AZ, USA 85711

BIRCHES and Lunarcubes: Building the First Deep Space Cubesat Broadband IR Spectrometer

Pamela Clark*[a], Robert MacDowall[b], William Farrell[b], Cliff Brambora[b], Terry Hurford[b], Dennis Reuter[b], Eric Mentzell[b], Deepak Patel[b], Stuart Banks[b], David Folta[b], Noah Petro[b], Benjamin Malphrus[c], Kevin Brown[c], Carl Brandon[d], Peter Chapin[d]
[a]California Institute of Technology Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109; [b]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771; [c]Morehead State University, Space Science Center, Morehead, KY 40351; [d]Vermont Technical College, Randolph Center, VT 05061

*Pamela.E.Clark@jpl.nasa.gov; phone 1 818 393-3262; fax 1 818 354-8887; jpl.nasa.gov

ABSTRACT

The Broadband InfraRed Compact High-resolution Exploration Spectrometer (BIRCHES), which will be described in detail here, is the compact broadband IR spectrometer of the Lunar Ice Cube mission. Lunar Ice Cube is one of 13 6U cubesats that will be deployed by EM1 in cislunar space, qualifying as lunarcubes. The LunarCube paradigm is a proposed approach for extending the affordable CubeSat standard to support access to deep space via cis-lunar/lunar missions. Because the lunar environment contains analogs of most solar system environments, the Moon is an ideal target for both testing critical deep space capabilities and understanding solar system formation and processes. Effectively, as developments are occurring in parallel, 13 prototype deep space cubesats are being flown for EM1. One useful outcome of this 'experiment' will be to determine to what extent it is possible to develop a lunarcube 'bus' with standardized interfaces to all subsystems using reasonable protocols for a variety of payloads. The lunar ice cube mission was developed as the test case in a GSFC R&D study to determine whether the cubesat paradigm could be applied to deep space, science requirements driven missions, and BIRCHES was its payload. Here, we present the design and describe the ongoing development, and testing, in the context of the challenges of using the cubesat paradigm to fly a broadband IR spectrometer in a 6U platform, including minimal funding and extensive need for leveraging existing assets and relationships on development, the foreshortened schedule for payload delivery on testing, and minimum bandwidth translating into simplified or canned operation.

Keywords: cubesat, broadband IR, lunarcubes, lunar orbiter, 6U, EM1

1. INSTRUMENT OVERVIEW

The versatile GSFC-developed payload BIRCHES (**Figure 1**), Broadband (1 to 4 micron) InfraRed Compact, High-resolution Exploration Spectrometer, is a miniaturized version of OVIRS (Osiris-Rex Visible InfraRed Spectrometer) on OSIRIS-Rex **[1]**. BIRCHES is a compact (1.5U, 2 kg, 12-25 W) point spectrometer with a compact cryocooled HgCdTe focal plane array for broadband measurements. The instrument includes an IRIS/AIM microcryocooler and controller **[2]**. The instrument will achieve sufficient SNR (>100) and spectral resolution (10 nm) through the use of a Linear Variable Filter to characterize and distinguish several spectral features associated with water in the 3-micron region, and potentially other volatiles already detected by LCROSS (H_2S, NH_3, CO_2, CH_4, OH, organics) and mineral bands. Typical footprint size will be 10 x 10 km, but will be somewhat smaller at the equator and larger toward the poles. We are also developing compact instrument electronics that can be easily reconfigured to support future instruments with Teledyne H1RG focal plane arrays **[1]** in 'imager' mode, when the communication downlink bandwidth becomes available. The instrument will enable the Lunar Ice Cube (**Figure 2**) mission science goals: determination of composition and distribution of volatiles in lunar regolith as a function of time of day, latitude, regolith age and composition, and thus enable understanding of current dynamics of lunar volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles.

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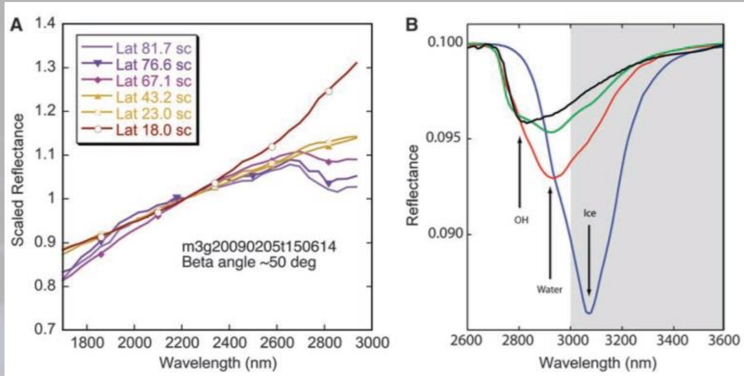
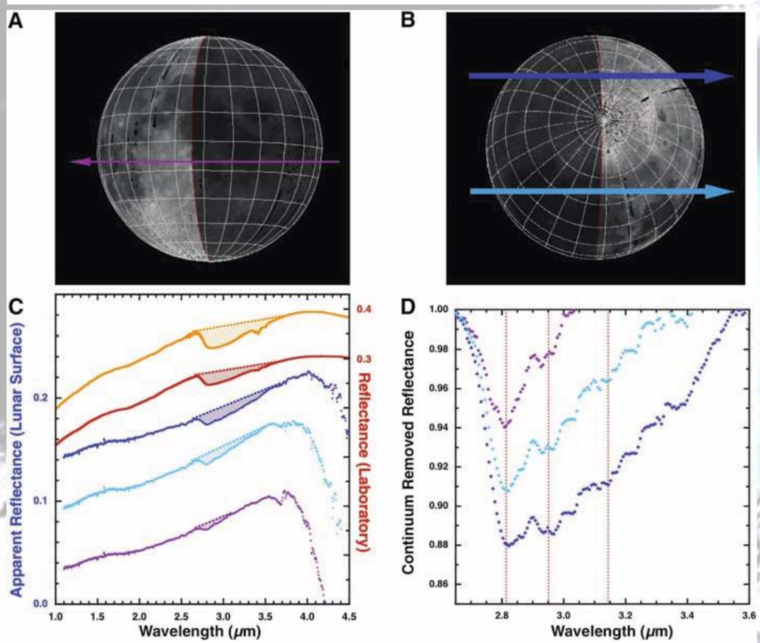
Significance of Water

Relevance to NASA	Growing Evidence for Global Distribution
HEOMD Strategic Knowledge Gaps: 1) Temporal Variability and Movement Dynamics of **Surface-Correlated OH and H2O** deposits toward permanently shadowed area retention (Lunar Ice Cube) 2) Composition, Form and Distribution of **Polar Volatiles (Lunar Flashlight, LunaH Map)** 3)Quality/quantity/distribution/form of **H species and other volatiles** in **mare and highlands regolith (Lunar Ice Cube)** **SMD Decadal Survey**: understanding solar system formation, and evolution of the **lunar** surface and atmosphere by further establishing the **role of surface volatiles** **SMD Scientific Context for Exploration of the Moon**: Using the Moon to study regolith, **exosphere (including water vapor)** processes on airless bodies	Evidence for surface ice near both poles (cold traps). Evidence for bound water in volcanic deposits. Evidence for hydroxyl (OH) and water varying as function of of temperature (local time of day) and illumination (slope orientation) in 100's of PPM range.

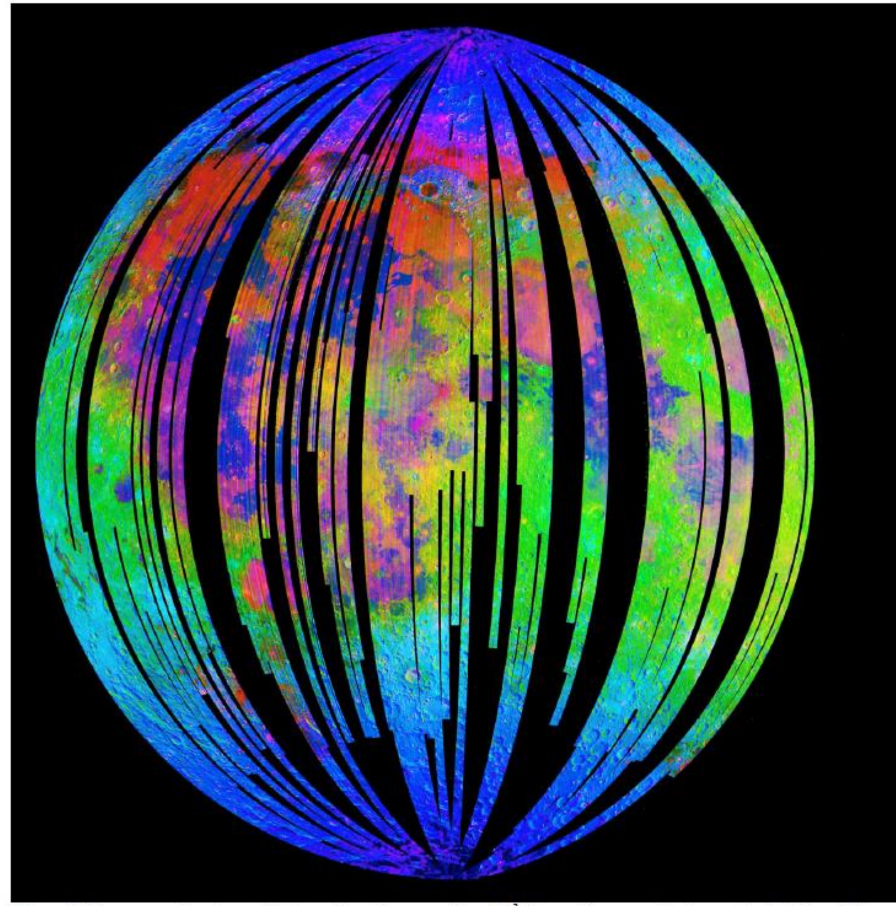
Evidence for Water



Reflectance spectra showing water and hydroxyl aborption features (near 3 microns) depth as a function of latitude. Chandrayaan M3, Pieters et al 2009

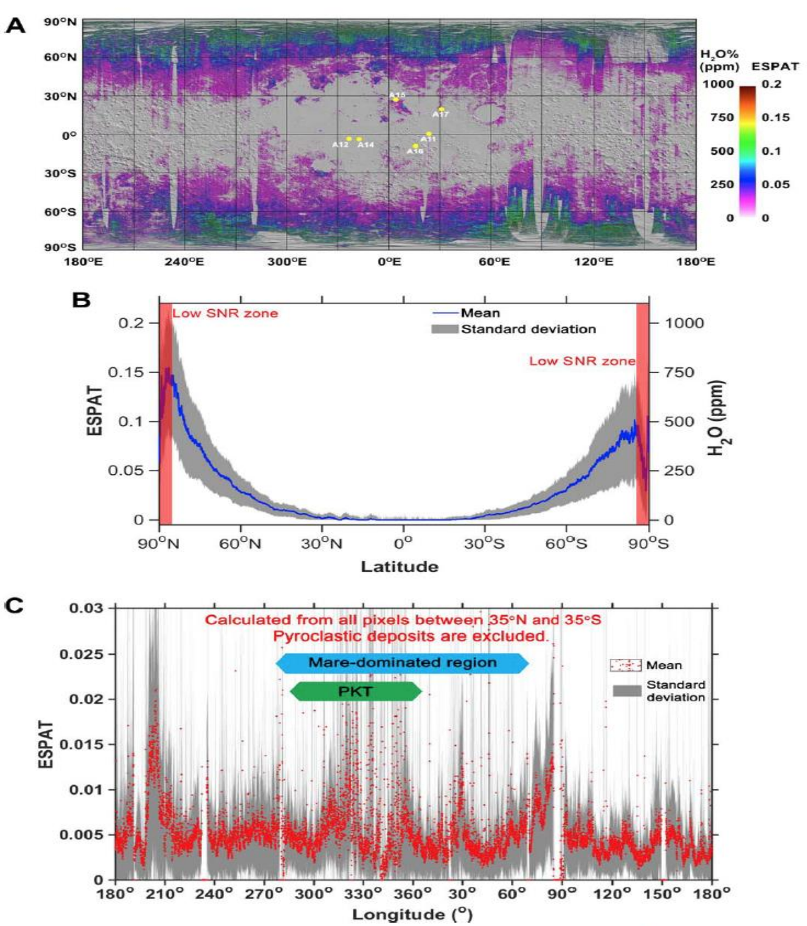


Reflectance spectra with absorption feature strength correlated with time of day. Deep Impact Epoxi. Sunshine et al 2009

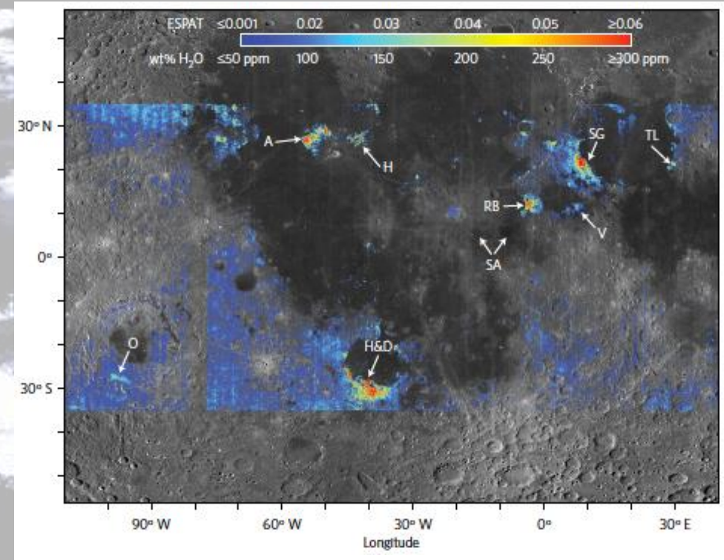


Water and Hydroxyl on Moon. Combined Red (Pyroxene), Green (Reflectance continuum), Blue (water and hydroxyl absorption) bands. Blue, Cyan, Magenta, Pink water indicators. Chandrayaan M3, Pieters et al 2009

Evidence for Water



M3 calculated ESPAT estimated water content (Apollo landing sites in yellow) map (A), all longitude-averaged latitude profile (B), and +/- 35 degree latitude-averaged longitude profile (C). Li and Milliken, 2017.



Map of 2.85 u Effective Single Particle Absorption Thickness (ESPAT) derived from M3 at low lunar latitudes. Features apparently associated with pyroclastic deposits, lending credence to hypothesis of volatile-rich (hundreds ppm) sources in mantle. A aristarchus; O orientale, RB Rima Bode, SG Sulpicius Gallus, TL Taur-Littrow. Milliken and Li, 2017.

Evidence for Water

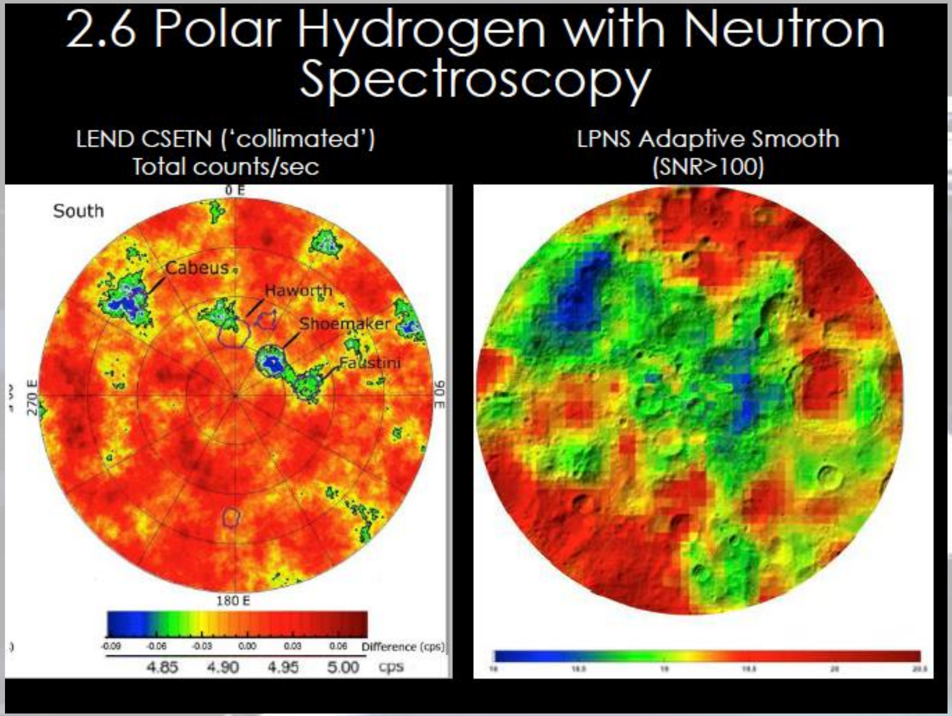
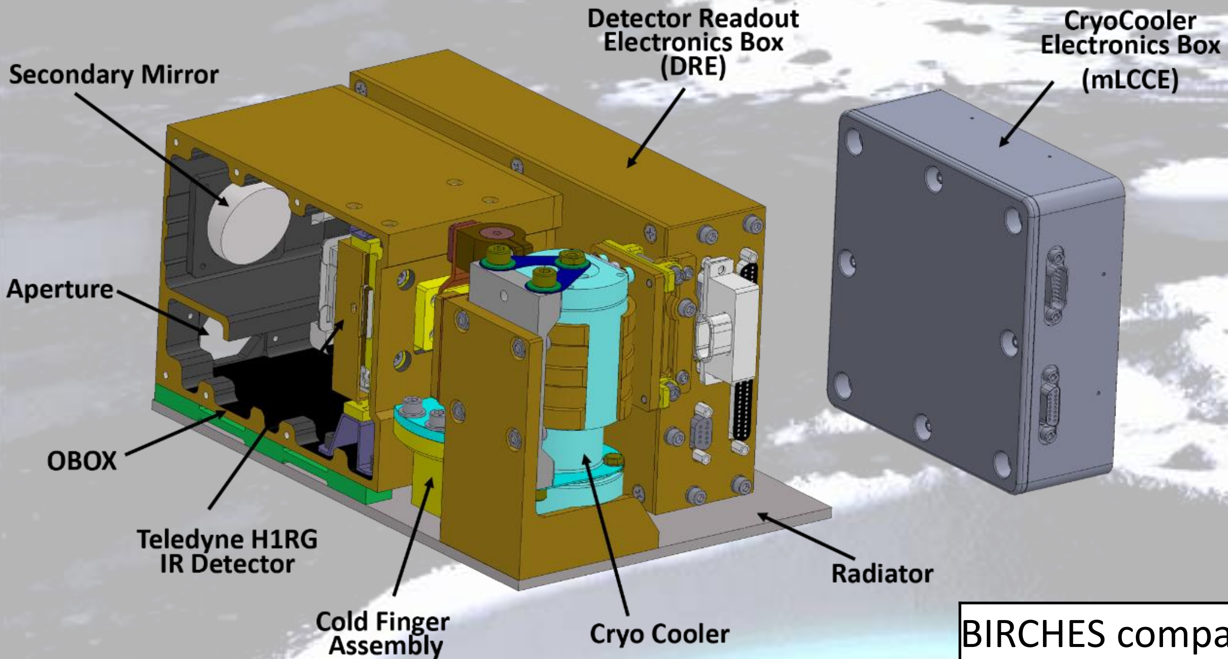


Table B.2 IR measured volatile abundance in LCROSS plume (Colaprete et al, 2010)		
Compound	Molecules cm^{-2}	Relative to $H_2O(g)$*
H2O	5.1(1.4)E19	100%
H2S	8.5(0.9)E18	16.75%
NH3	3.1(1.5)E18	6.03%
SO2	1.6(0.4)E18	3.19%
C2H2	1.6(1.7)E18	3.12%
CO2	1.1(1.0)E18	2.17%
CH2OH	7.8(4.2)E17	1.55%
CH4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%
*Abundance as described in text for fit in Fig 3C		

Technology Goals
Demonstrate Enabling Technologies for Interplanetary Cubesats

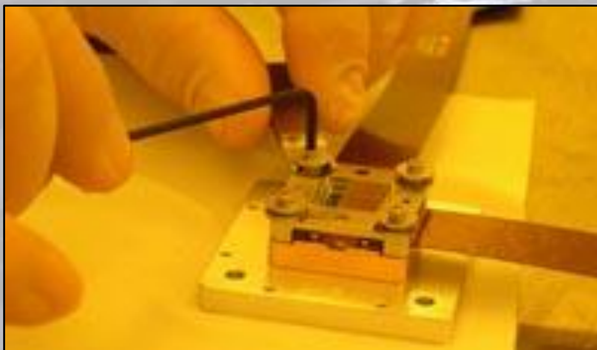
- **Lunar Ice Cube and LunaH Map Busek BIT 3** - High isp RF Ion Engine
- **BIRCHES** Miniaturized (from OVIRS) broadband IR Spectrometer with integrated microcryocooler completely capturing the 3 micron region with several features of interest.
- **Space Micro C&DH-** Inexpensive Radiation-tolerant Subsystem
- **Lunar Ice Cube and LunaH Map: BCT- XACT/-XB1 bus** ADCS (Star Tracker, Reaction Wheels
- **Lunar Ice Cube and LunaH Map: JPL Iris v. 2.1** Ranging Transceiver
- Planetary (PDS) Archiving on a limited budget

Lunar Ice Cube Instrument - BIRCHES IR SPECTROMETER

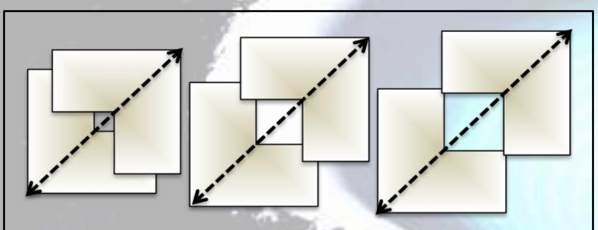


BIRCHES compactness		
Property	Ralph	BIRCHES
Mass kg	11	3
Power W	5	#10-20 W
Size cm	49 x 40 x 29	10 x 10 x 15
# includes 3 W detector electronics, 1.5 W AFS controller, 5-10 W cryocooler		

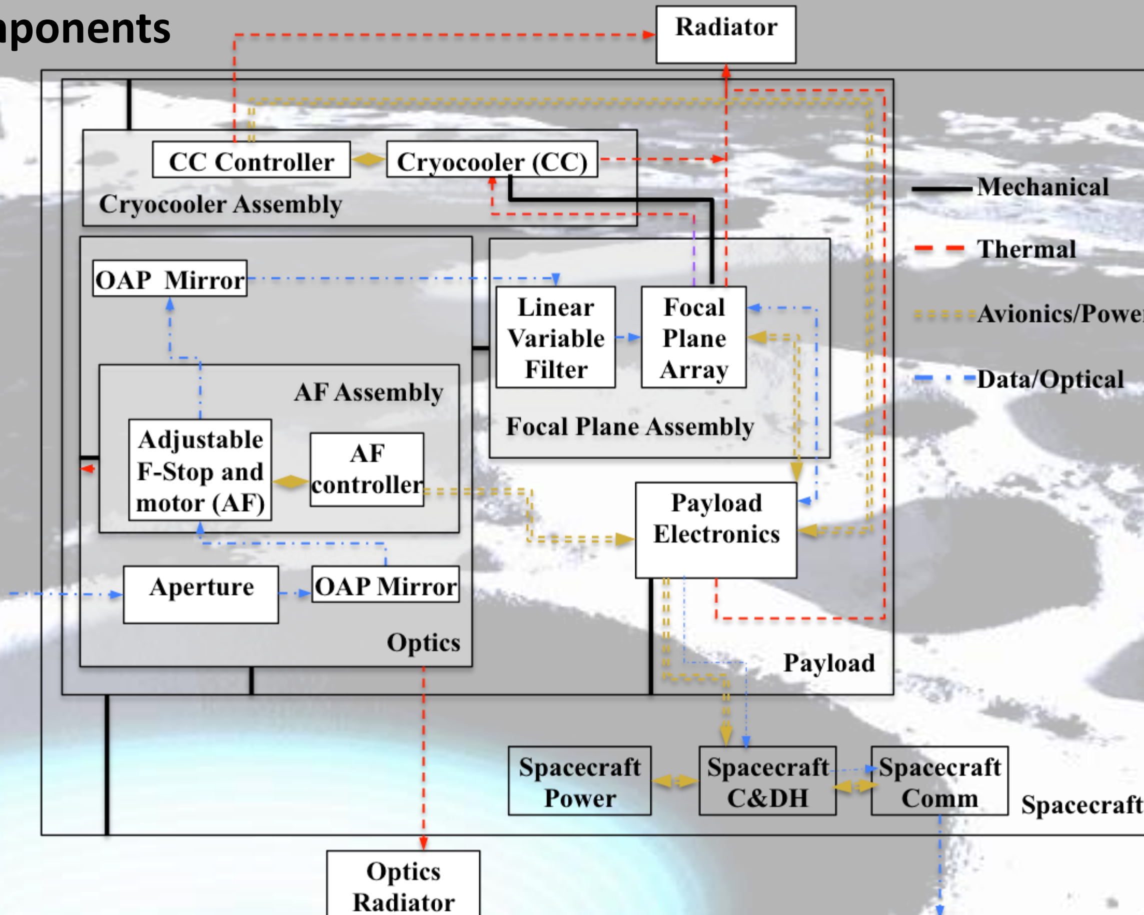
Spectrometer Schematic and Components



BIRCHES utilizes a compact Teledyne H1RG HgCdTe Focal Plane Array and JDSU linear variable filter leveraging OSIRIS REx OVIRS.



Adjustable Iris maintains footprint size at 10 km by varying FOV regardless of altitude



BIRCHES Analog Processing Unit (APU) (top)

COTS AFRL developed AIM SX030 microcryocooler with cold finger to maintain detector at ≤115K and iris controller

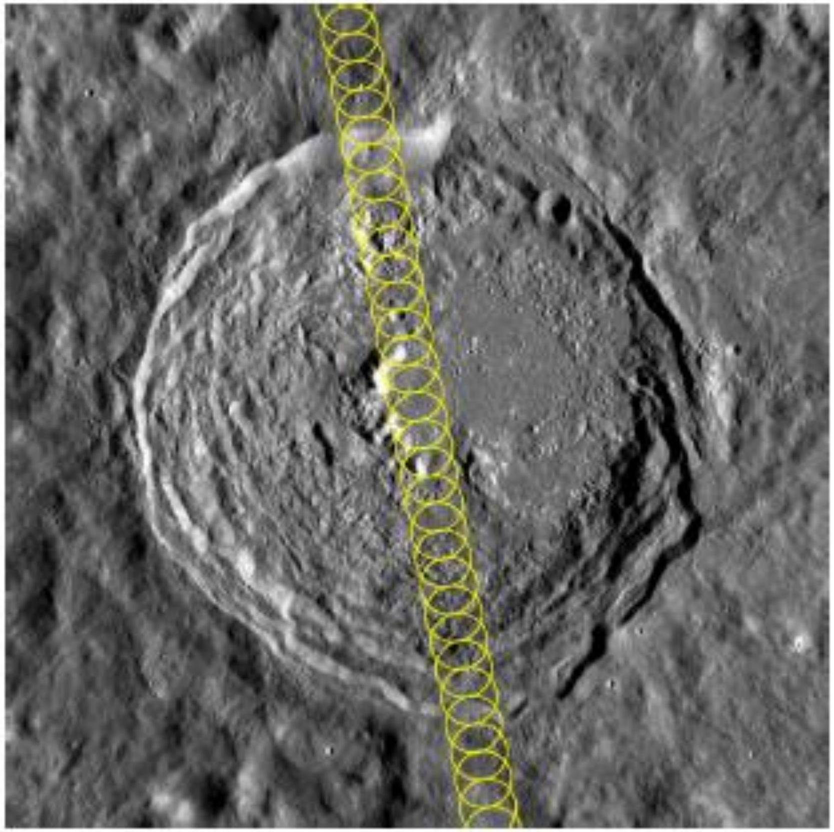
Species	µm	description
Water Form, Component		
water vapor	2.738	OH stretch
	2.663	OH stretch
liquid water	3.106	H-OH fundamental
	2.903	H-OH fundamental
	1.4	OH stretch overtone
	1.9	HOH bend overtone
	2.85	M3 Feature
	2.9	total H_2O
hydroxyl ion	2.7-2.8	OH stretch (mineral)
	2.81	OH (surface or structural) stretches
	2.2-2.3	cation-OH bend
	3.6	structural OH
bound H_2O	2.85	Houck et al (Mars)
	3	H_2O of hydration
	2.95	H_2O stretch (Mars)
	3.14	feature w/2.95
adsorbed H_2O	2.9-3.0	R. Clark
ice	1.5	band depth-layer correlated
	2	strong feature
	3.06	Pieters et al
Other Volatiles		
NH_3	1.65, 2. 2.2	N-H stretch
CO_2	2, 2.7	C-O vibration and overtones
H_2S	3	
CH_4/organics	1.2, 1.7, 2.3, 3.3	C-H stretch fundamental and overtones
Mineral Bands		
pyroxene	0.95-1	crystal field effects, charge transfer
olivine	1, 2, 2.9	crystal field effects
spinels	2	crystal field effects
iron oxides	1	crystal field effects
carbonate	2.35, 2.5	overtone bands
sulfide	3	conduction bands
hydrated silicates	3-3.5	vibrational processes
anticipate wavelength of peak for water absorption band to be structural<bound<adsorbed<ice		

BIRCHES Observation Requirements

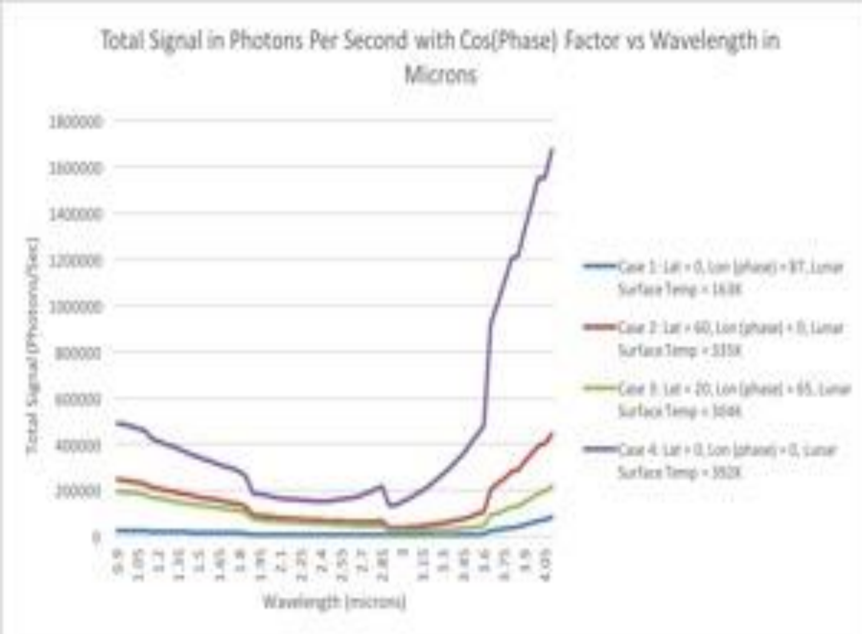
Requirement
A footprint of 10 km from an altitude of 100 km

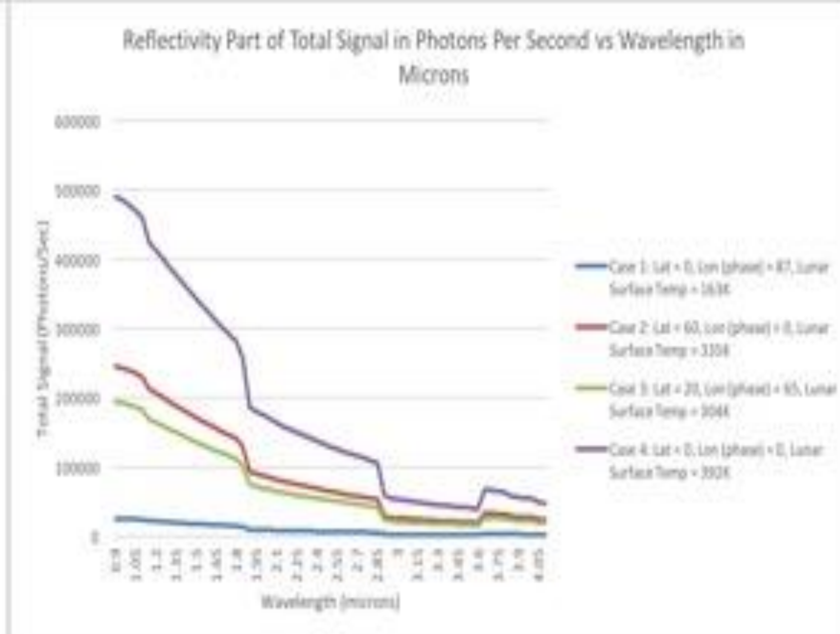
Footprint 10 km in along track direction regardless of altitude, consecutive observations separated by a couple of kilometers; greater overlap of consecutive tracks at poles, separted by a couple of kilometers

- FOV of the instrument will be 100 mrad (6°)
- An Adjustable Field Stop (AFS) shall maintain the FOV to 10 km in size
- Based on spacecraft velocity exposures shall be taken at intervals of 2.7 seconds (TBC)



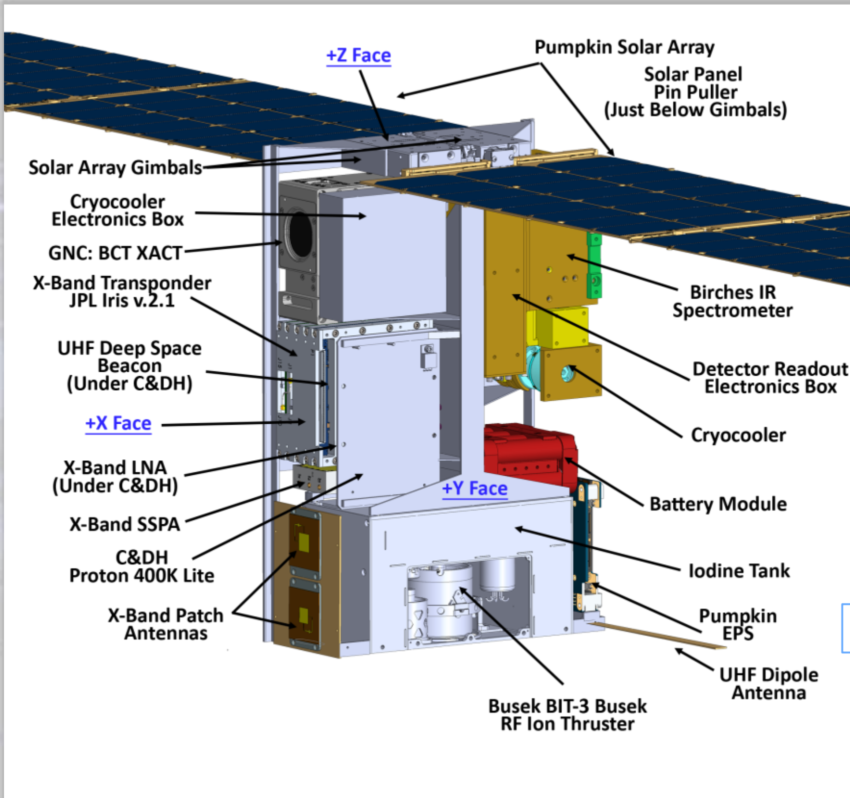
Vavilov Crater:
100 km in diameter
1° S, 138° W

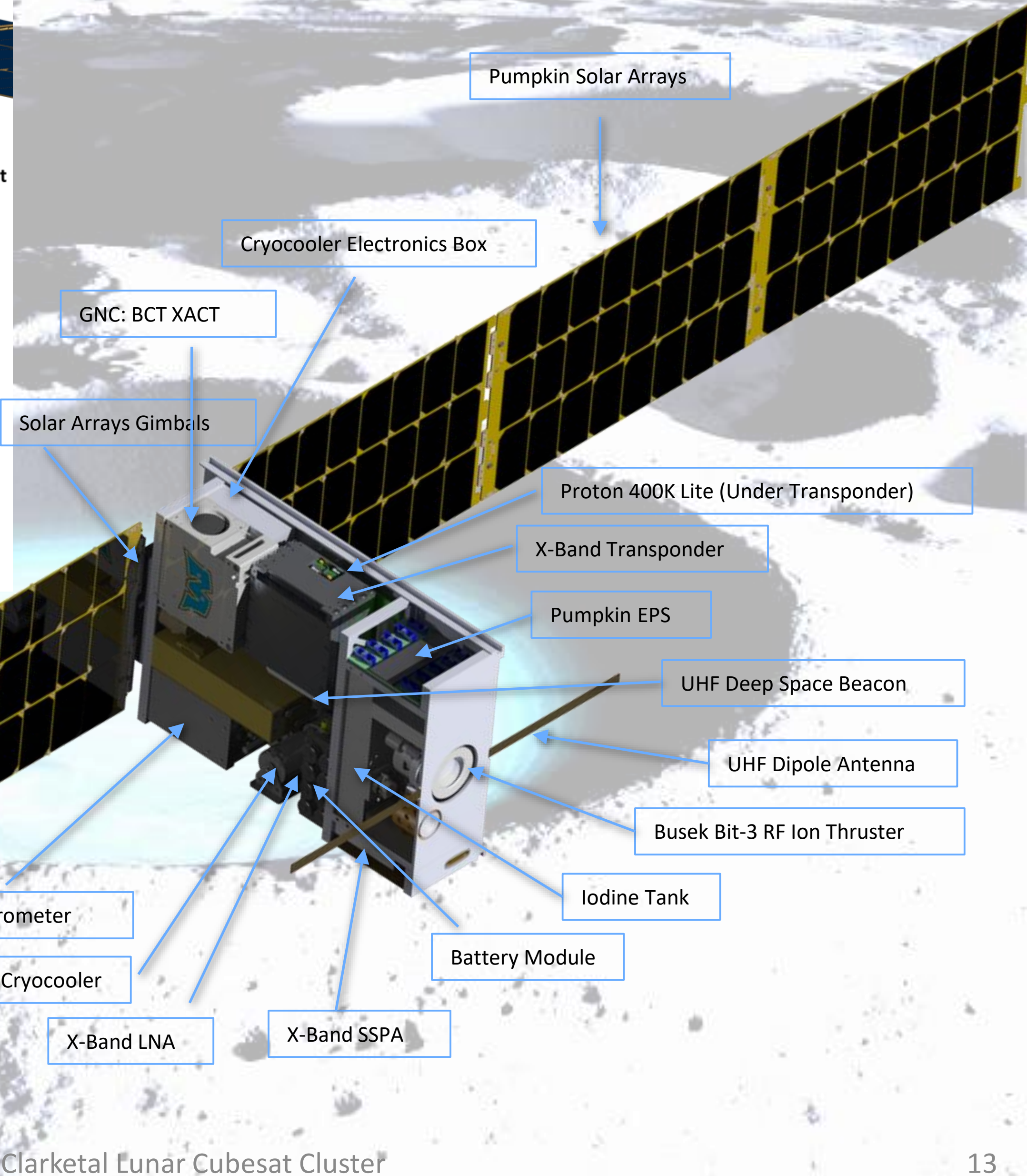




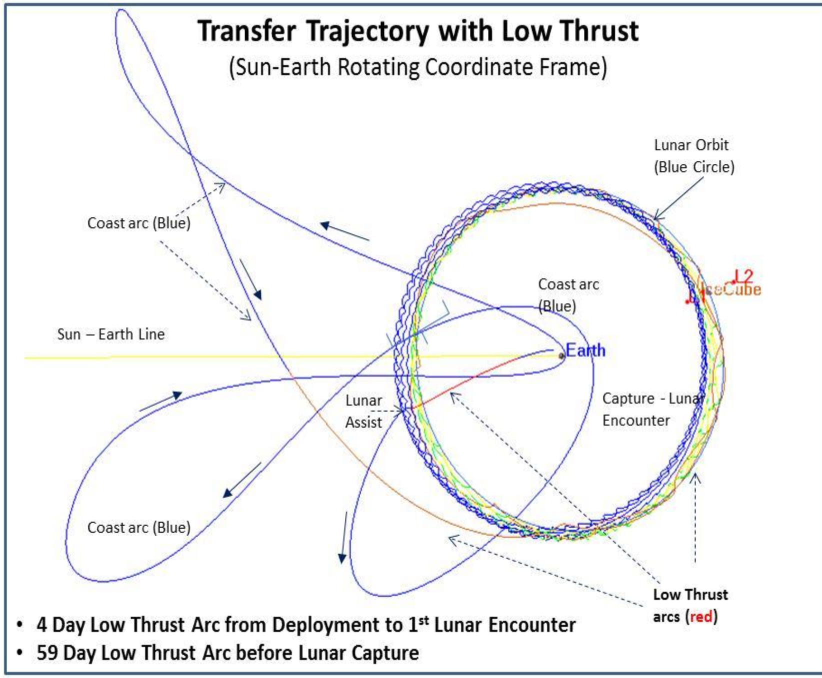
Case	Lat	ToD	Temp K	Reflectivity @ 3um photons/sec	Total Signal	SNR	Band depth/PPM water		
							0.1/1000	0.05/500	0.01/100
1	0	87	163	3254	2760	52	276	138	27
2	60	0	335	39045	26400	162	2640	1320	264
3	20	65	304	24279	20963	145	2096	1480	210
4	0	0	395	150777	52800	230	5280	2640	528

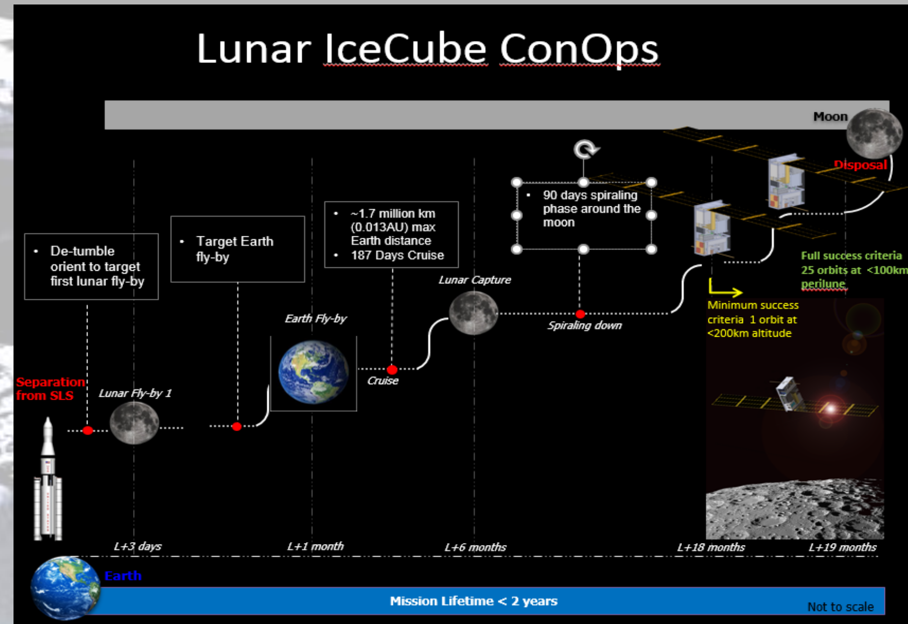
Lunar Ice Cube Bus

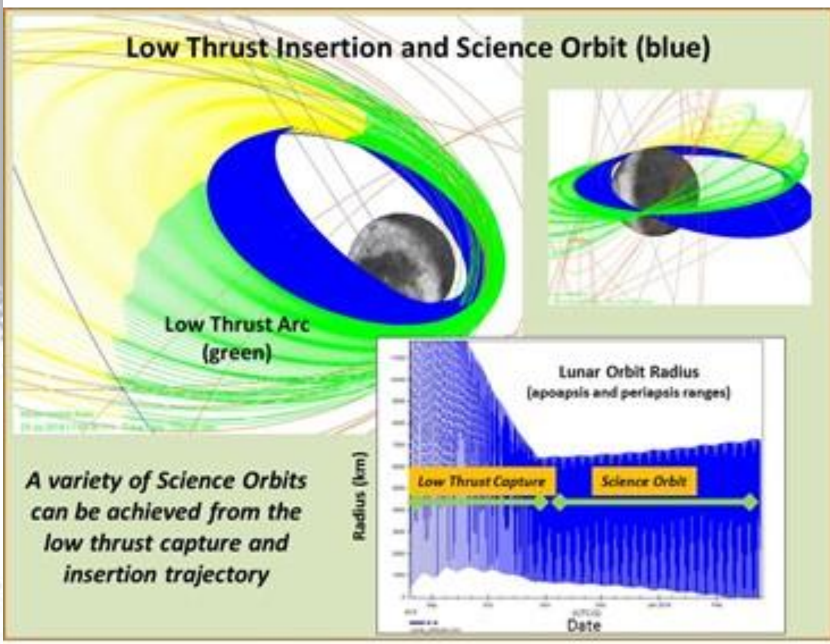


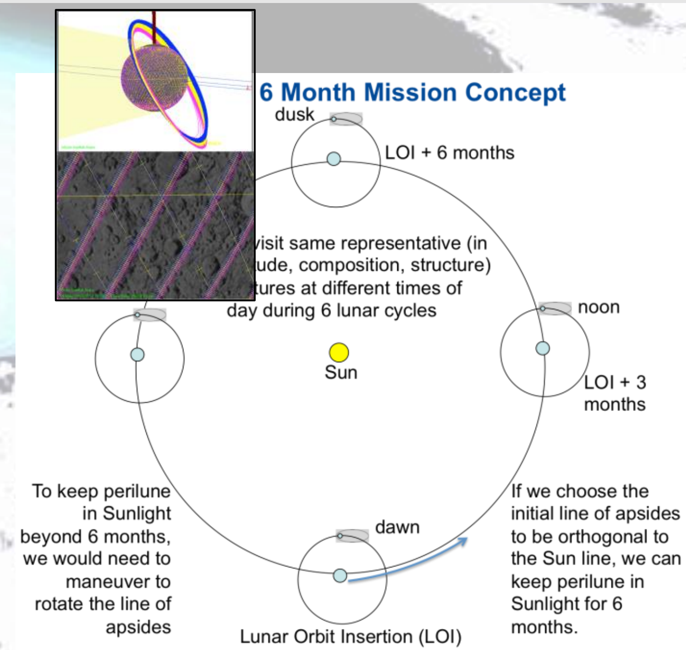


Lunar Ice Cube MIssion Concept







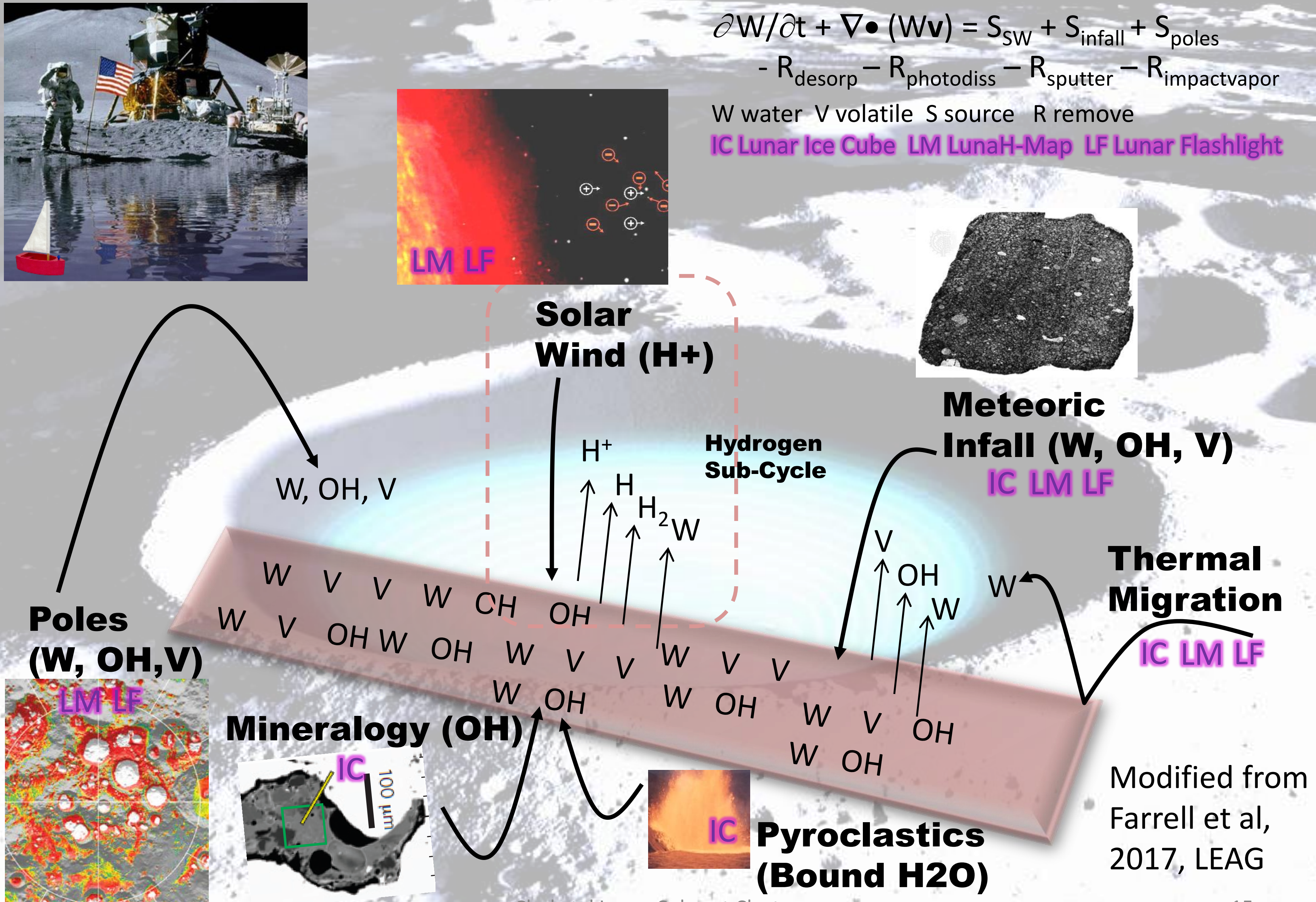


A Lunar Water System

$$\partial W/\partial t + \nabla \bullet (W\mathbf{v}) = S_{SW} + S_{infall} + S_{poles} - R_{desorp} - R_{photodiss} - R_{sputter} - R_{impactvapor}$$

W water V volatile S source R remove

IC Lunar Ice Cube LM LunaH-Map LF Lunar Flashlight



Modified from Farrell et al, 2017, LEAG

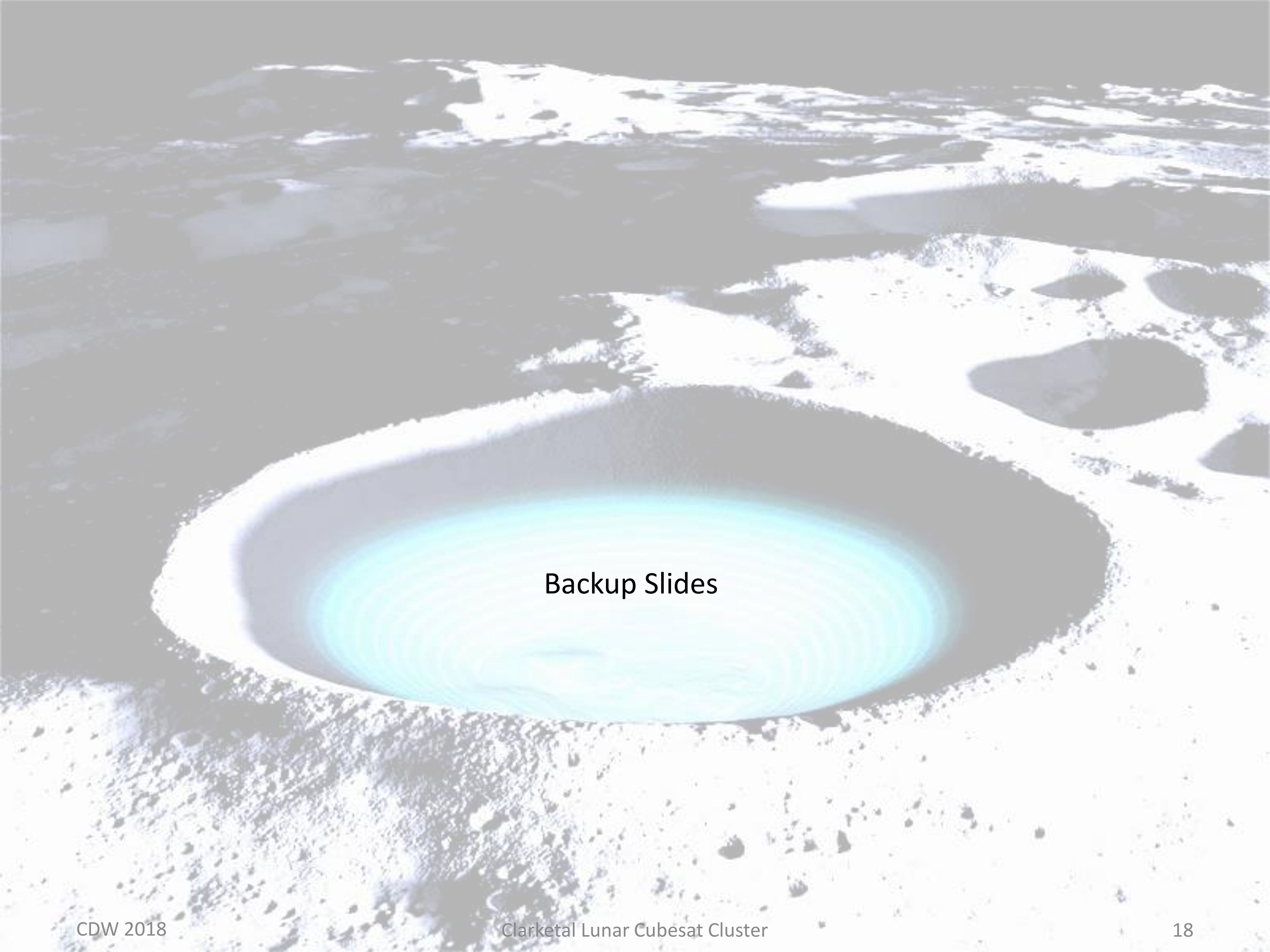
Conclusions

- Lunar Ice Cube will provide measurements for liquid water, ice, OH distribution across the lunar surface as function of time of day (temperature and illumination) for several lunar cycles for pole to pole swaths of the lunar surface to provide a basis for understanding global water dynamics.
- Lunar Flashlight will provide direct measurements of surface ice near the poles at the highest resolution (1 km), and LunaH-Map measurements from which surface and subsurface ice (down to 10's of cm) can be inferred at the poles.
- Some temporal overlap between LunaH-Map and Lunar Ice Cube will be useful in constraining the water migration process. Spatial overlap between LunaH-Map and Lunar Flashlight will be useful in constraining cold trap evolutionary processes.
- Regardless of the degree of overlap in space or time, these measurements when combined will provide far more systematic understanding of the water cycle, and the accessibility of water as a resource on the Moon.
- The three missions will act as a de facto multi-platform cluster for measuring lunar volatiles, yet another way in which the first deep space cubesats are demonstrating not only new technologies but new approaches to scientific exploration.
- We are doing what cubesats are supposed to do: creating an innovative and tailored solution with a standard platform.

LunarCubes Still Around!!!!

Your challenging science mission requirements needed

pamela.e.clark@jpl.nasa.gov



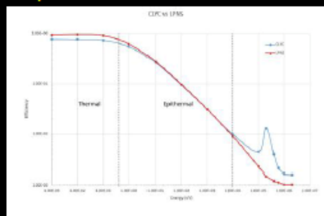
Backup Slides

LunaH-Map Instrument

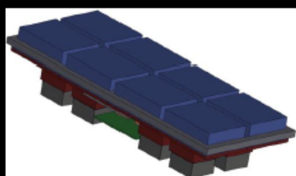
Hardgrove et al, 2017, LEAG and 2nd GSFC planetary cubesat workshop

3. LunaH-Map Neutron Spectrometer

Mini-NS will have two 100-cm² CLYC arrays (200cm² total). A thin Cd foil will be used for epithermal neutron detection

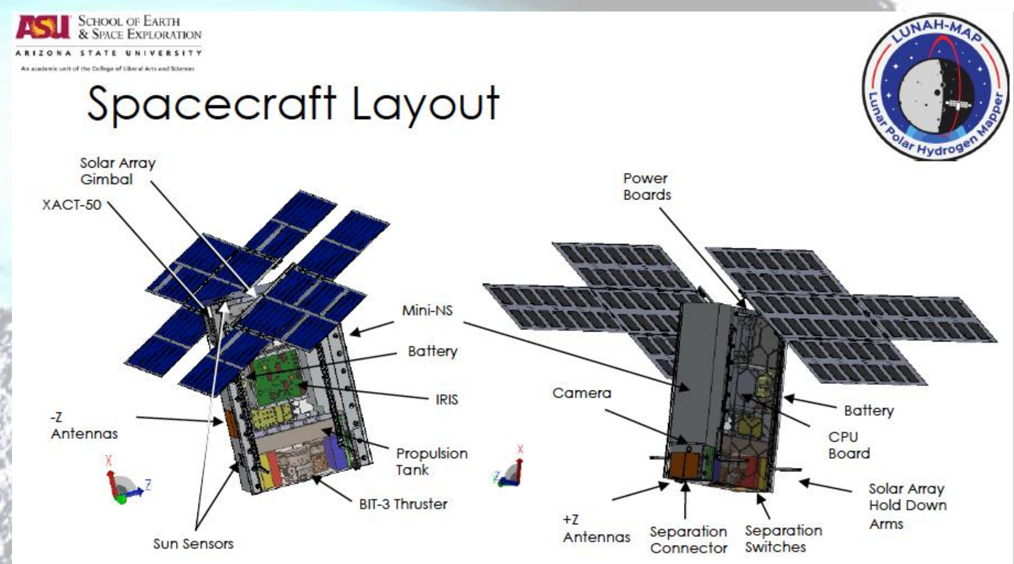


LunaH-Map Mini-NS (2cm) compared to 5.7-cm diameter LPNS ^{3}He counter



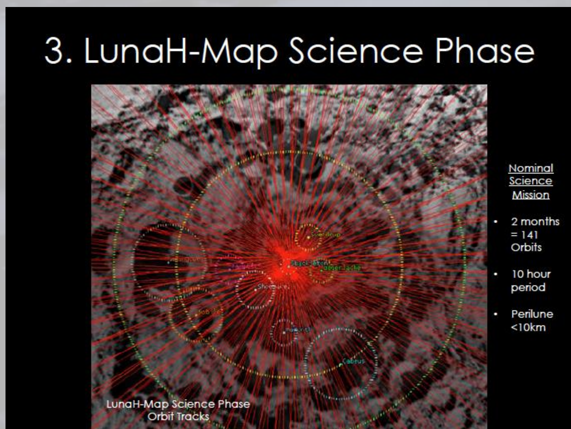
Preliminary design of Mini-NS for LunaH-Map

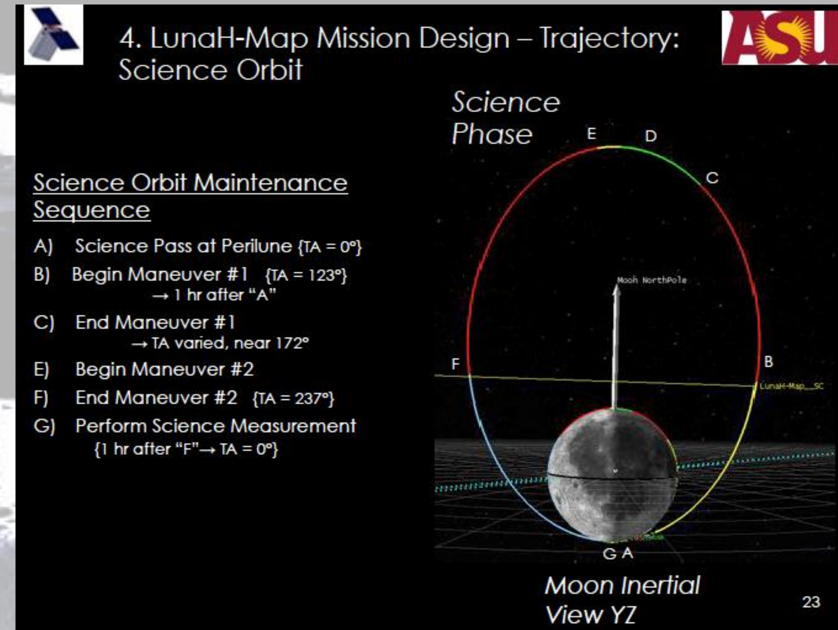
Specifications	
Detector	2, 4x4 Detector Arrays of CLYC (each 2.5cm x 2.5cm x 2cm)
Sensitivities	Thermal (<0.3 eV) and epithermal (with Cd shield) neutrons and 3.9% FWHM at 662 keV
Dimensions	27.94 cm x 11.43cm x 6cm
Mass	2.6 kg
Power	2 Watts (during data acquisition); 0.35 Watts (idle)
Data Acquisition Times	Counts binned every 3 seconds
Data Volume	<1 Mbit for mission duration

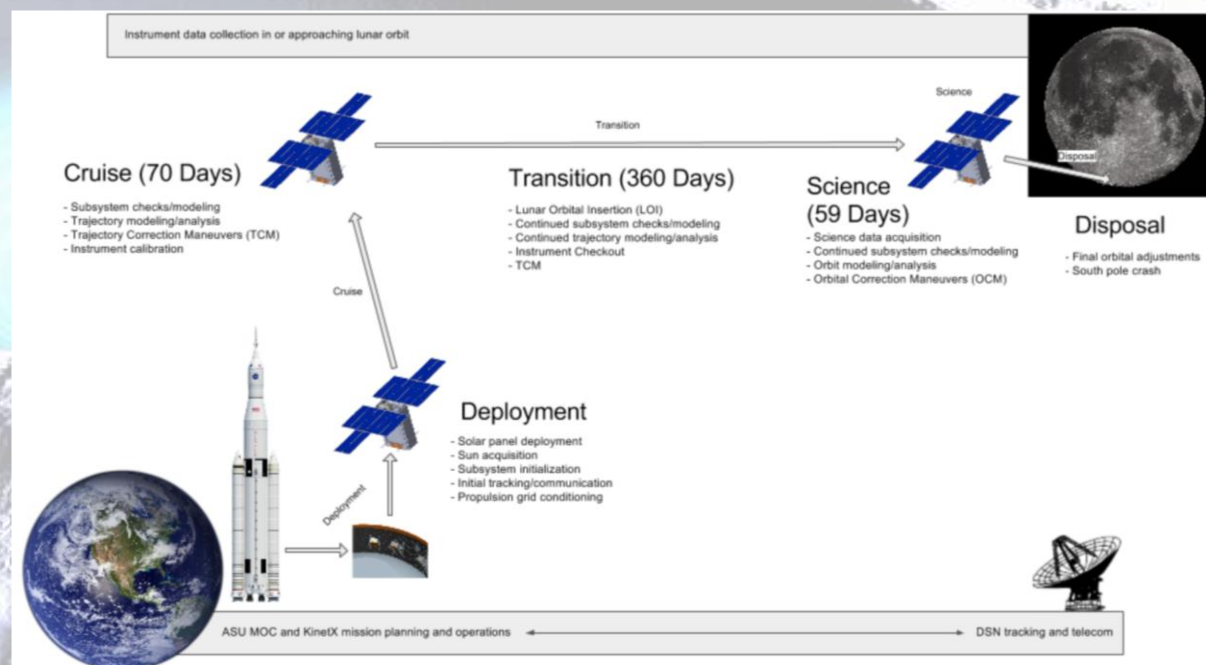


LunaH-Map Mission Concept

Hardgrove et al, 2017, LEAG and 2nd GSFC planetary cubesat workshop

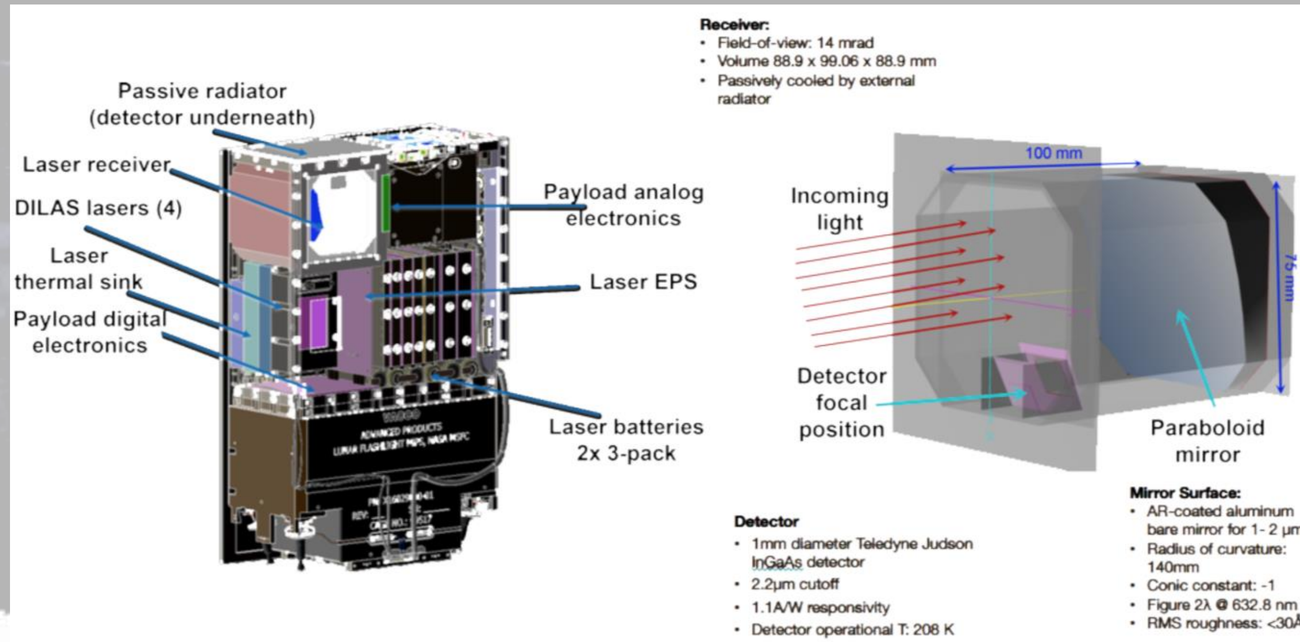


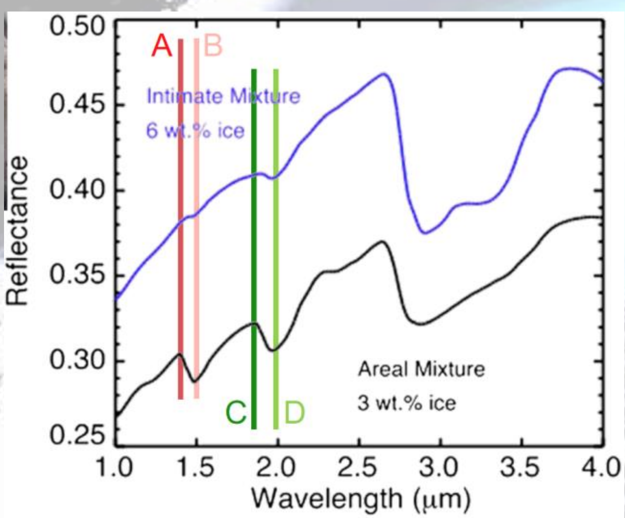


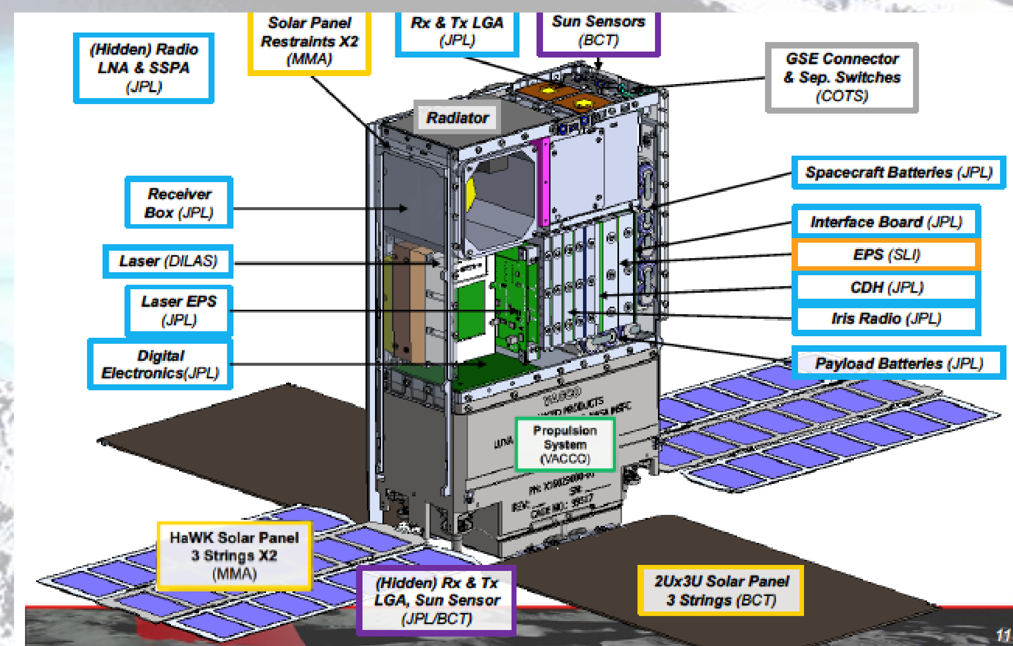


Lunar Flashlight Instrument

Cohen et al, 2017, LEAG







Lunar Flashlight Instrument

Cohen et al, 2017, LEAG