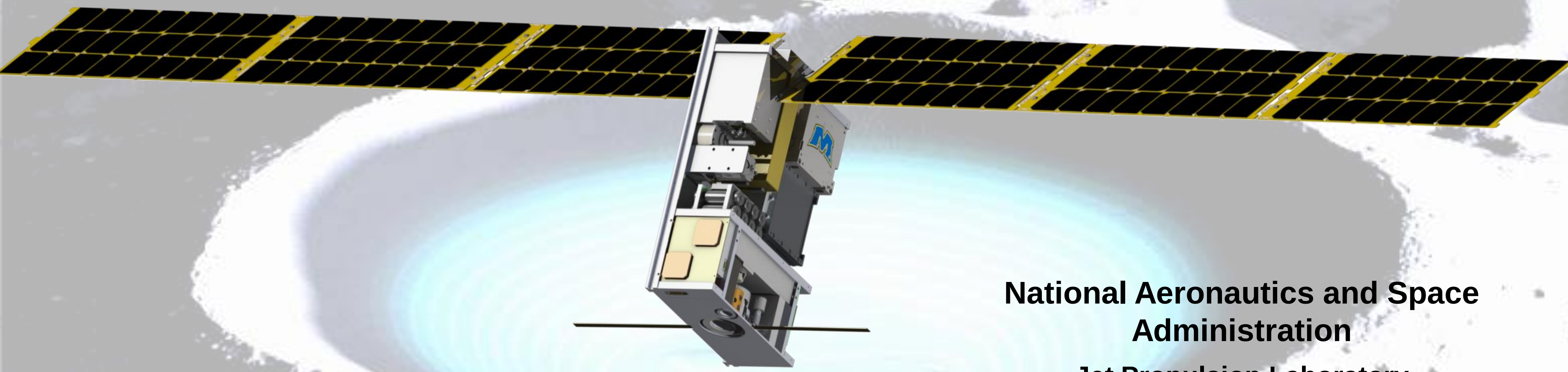
Lunar Ice Cube: Ongoing Development of First Generation Deep Space CubeSat Mission with Compact broadband IR Spectrometer

P.E. Clark (Science PI) (CalTech/JPL),
B.Malphrus (PI), K. Brown (SE), J. Schabert, S. McNeil, B. Micula (Morehead State U),
C. Brambora, G. Young, N. Gorius, T. Hewagama, D. Patel, T. Hurford, D. Folta, P. Mason (NASA/GSFC)
and members of the Lunar ICe Cube Team



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Current Status

Shutdown delay.

EM1 Launch now late 2021.

Publications (Source): Online Presentations, Short papers from 2015 at LPSC, LEAG, CDW, and Interplanetary SmallSat Conference. Papers, Clark et al, 2016, 2018, 2019, SPIE Optics; 2018 Small Satellite Conference.

Performing I&T for Lunar Ice Cube subsystems as delivered to Morehead. BIRCHES now undergoing optical, digital, and radiometric calibration in simulated environment

FlatSat with emulators testing all subsystems

End to End tests scheduled for fall.

Ready for Data System testing for Level 0 data production this fall. Level 1 data analysis software under development.

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

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Cubesats in Cislunar Space

Pamela Clark
California Institute of Technology/Jet Propulsion Laboratory
MS 306/43,14800 Oak Grove Drive, Pasadena, Ca 91109; 818-393-3262;
pamela.e.clark@jpl.nasa.gov

ABSTRACT

Within the next three years, at least 15 deep space cubesat 'prototypes' will have been launched, testing the viability of cubesat paradigm in deep space. Three of the EM1-deployed cubesat missions, the first de facto deep space cubesat 'cluster', will be science requirements driven lunar orbiters with remote sensing instruments for lunar surface/subsurface volatile characterization. These include: Lunar Ice Cube (1-4 micron broadband IR spectrometer and microcryocooler, volatile distribution as a function of time of day), Lunar Flashlight (active source laser and

Nature of and Lessons Learned from Lunar Ice Cube and the First Deep Space Cubesat 'Cluster'

Pamela Clark*[a], Robert MacDowall[b], William Farrell[b], Cliff Brambora[b], Al Lunsford[b], Terry Hurford[b], David Folta[b], Benjamin Malphrus[c], Matt Grubb[e], Sarah Wilzcewski**[a], Emily Bujold **[a]
[a]Jet Propulsion Laboratory, California Institute of Technology, 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]NASA IV&V, Fairmont, WV 26554

*Pamela.E.Clark@jpl.nasa.gov; phone 1 818 393-3262; fax 1 818 354-8887; jpl.nasa.gov
** Jet Propulsion Laboratory, California Institute of Technology, Student Interns from Morehead State University

ABSTRACT

Cubesats operating in deep space face challenges Earth-orbiting cubesats do not. 15 deep space cubesat 'prototypes' will be launched over the next two years including the two MarCO cubesats, the 2018 demonstration of dual communication system at Mars, and the 13 diverse cubesats being deployed from the SLS EM1 mission within the next two years. Three of the EM1 cubesat missions, including the first deep space cubesat 'cluster', will be lunar orbiters with remote sensing instruments for lunar surface/regolith measurements. These include: Lunar Ice Cube, with its 1-4 micron broadband IR spectrometer, BIRCHES, to determine volatile distribution as a function of time of day; Lunar Flashlight, to confirm the presence of surface ice at the lunar poles, utilizing an active source (laser), and looking for absorption features in the returning signal; and LunaH-Map to characterize ice at or below the surface at the poles with a compact neutron spectrometer. In addition, the BIRCHES instrument on Lunar Ice Cube will provide the first demonstration of a microcryocooler (AIM/IRIS) in deep space. Although not originally required to do so, all will be delivering science data to the Planetary Data System, the first formal archiving effort for cubesats. 4 of the 20 recently NASA-sponsored (PSDS3) study groups for deep space cubesat/smallsat mission concepts were lunar mission concepts, most involving 12U cubesats. NASA SIMPLEX 2/SALMON 3 AO will create ongoing opportunities for low-cost missions as 'rides' on government space program or private sector vehicles as these become available.

Keywords: Moon, cubesats, volatiles, Broadband IR, Neutrons, Laser, lunarcubes, lunar orbiters, 6U, EM1

1. LUNAR CUBESATS BEYOND LEO

Unlike their earth-orbiting predecessors, deep space cubesats are required to have the full functionality, and active control systems, of any spacecraft operating in deep space. 15 6U cubesats with diverse payloads entering deep space over the next two years have been (MarCO) or are being built (EM1 13), effectively 'prototypes' for deep space cubesats. Three of them, Lunar Ice Cube, Lunar Flashlight, and LunaH-Map, are science requirements-driven lunar orbiters with the goal of increasing our knowledge of lunar volatiles, acting as the first de facto deep space cubesat cluster.

Out of the 13 cubesats to be deployed by EM1 (Table 1) sometime during 2020, 8 are specifically designed for lunar or cislunar operation: Lunar Ice Cube, Lunar Flashlight, and LunaH Map, all of which will be described in more detail below. LunIR is a Lockheed Martin flyby which will perform IR thermography and demonstrate a new propulsion system. Omotenashi is a JAXA-sponsored semi-hard impactor and radiation environment monitor. NASA CubeQuest challenge selectees Team Miles (Tampa HackerSpace), CUE3 (U Colorado), and Cislunar Explorers (Cornell) will demonstrate communication and propulsion technologies in cislunar space. The compact Ion Analyzer and energetic neutral imagers instruments of the proposed Hydrogen Albedo Lunar Orbiter (HALO) received further development funds, through the NASA SIMPLEx program, and compact surface instruments were proposed for NASA's Development of Advanced Lunar Instruments (DALI) program, to be selected later in 2018. Meanwhile, two 12U cubesat missions, LUMIO (Meteoroid

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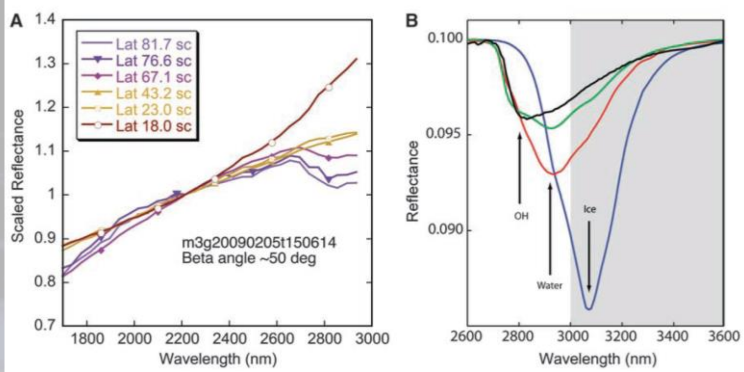
Significance of Water

Relevance to NASA	Growing Evidence for Global Distribution
HEOMD Strategic Knowledge Gaps: 1) Temporal Variability and Movement Dynamics of **Surface-Correlated OH and H_2O** 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) at >30 degrees latitude** **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 surface volcanic deposits. Evidence for surface 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 polar region bulk water down to 1 meter depth 100 PPM range, unknown distribution

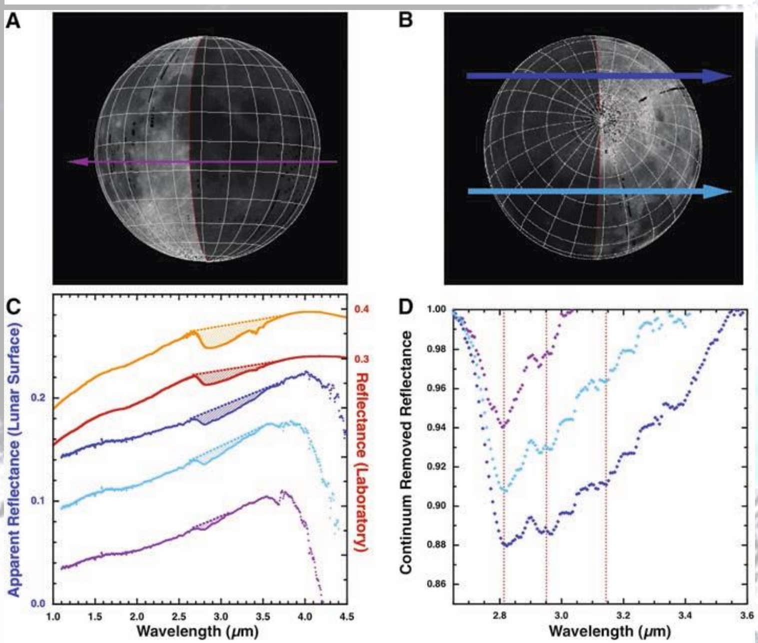
Table 1: Water-related absorption features. Yellow: features ~3 microns. Blue: Prominent water-related features near 1.5 and 2 microns.

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 H2O
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 H2O	2.85	Houck et al (Mars)
	3	H2O of hydration
	2.95	H2O stretch (Mars)
	3.14	feature w/2.95
adsorbed H2O	2.9-3.0	R. Clark
ice	1.5	band depth-layer correlated
	2	strong feature
	3.06	Pieters et al
Other Volatiles		
NH3	1.65, 2. 2.2	N-H stretch
CO2	2, 2.7	C-O vibration and overtones
H2S	3	
CH4/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.		

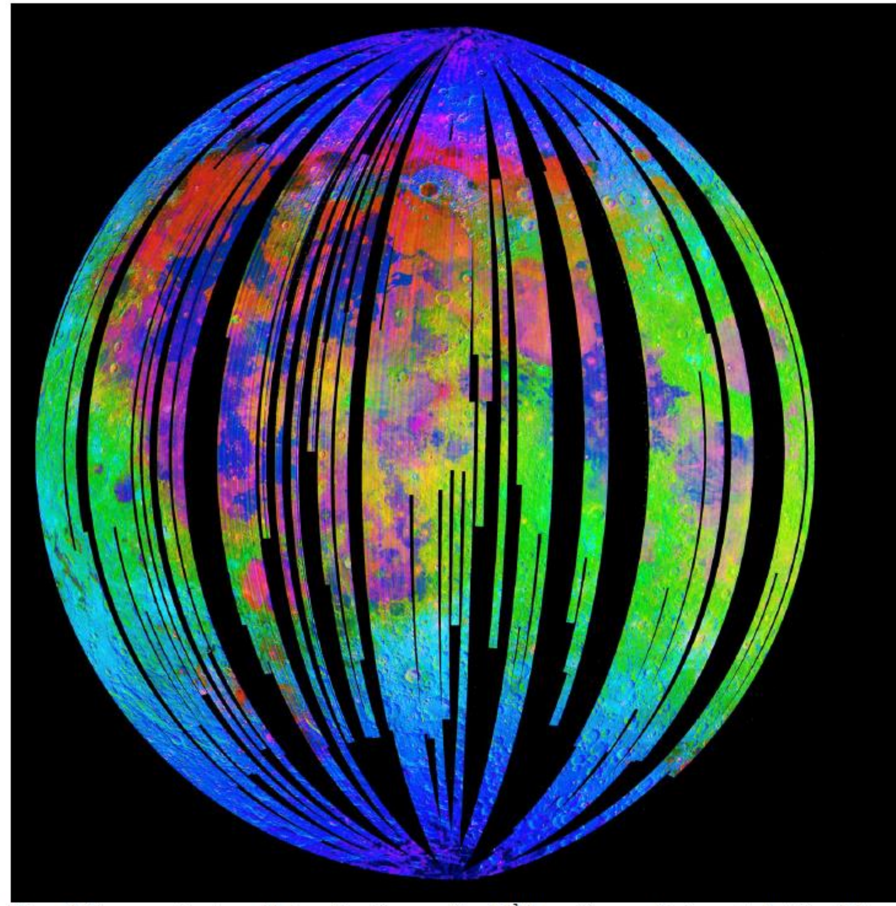
Evidence for Water



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

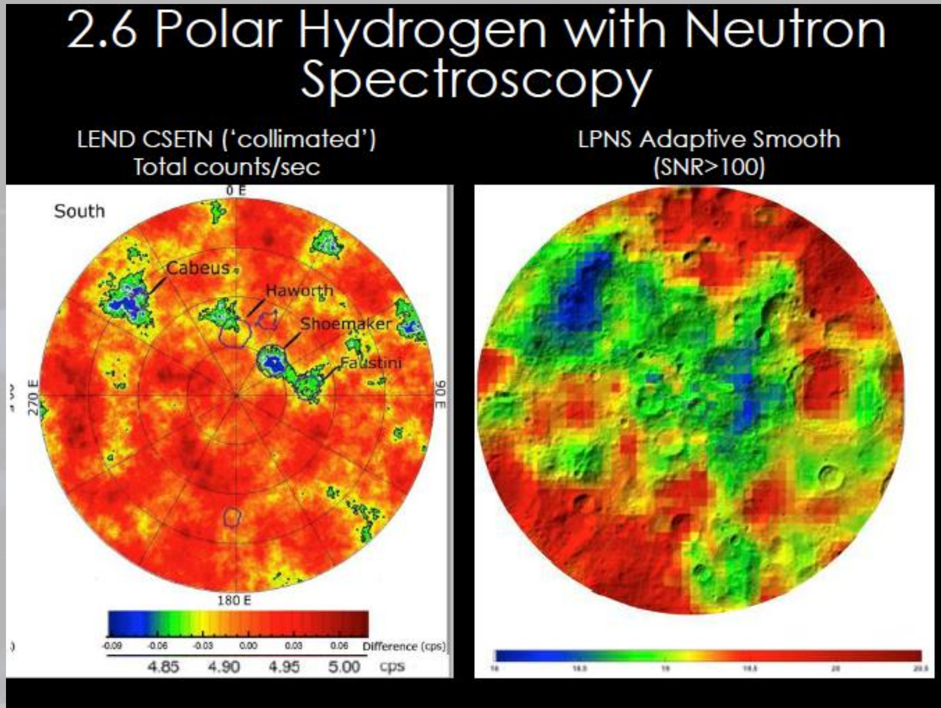
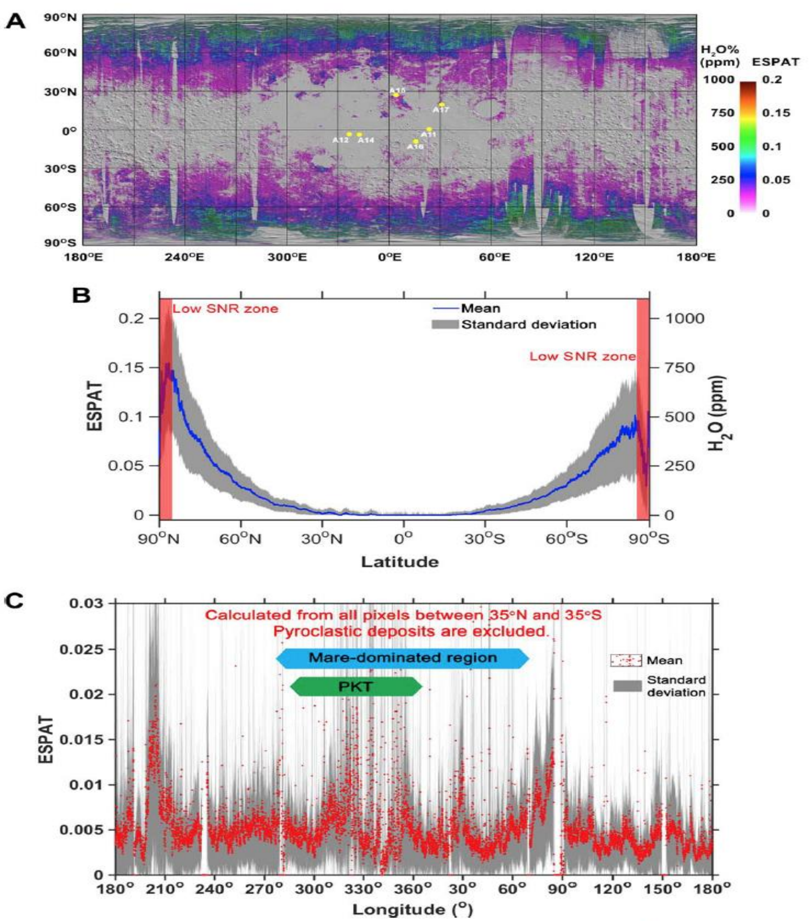
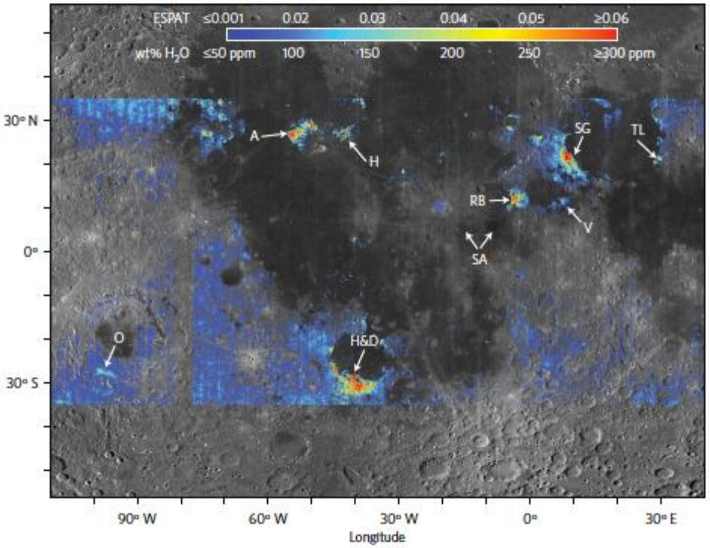


Table B.2 IR measured volatile abundance in LCROSS plume (Colaprete et al, 2010)		
Compound	Molecules cm^{-2}	Relative to $H_2O(g)$*
H2O	5.1(1.4)E19	100%
H2S	8.5(0.9)E18	16.75%
NH3	3.1(1.5)E18	6.03%
SO2	1.6(0.4)E18	3.19%
C2H2	1.6(1.7)E18	3.12%
CO2	1.1(1.0)E18	2.17%
CH2OH	7.8(4.2)E17	1.55%
CH4	3.3(3.0)E17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

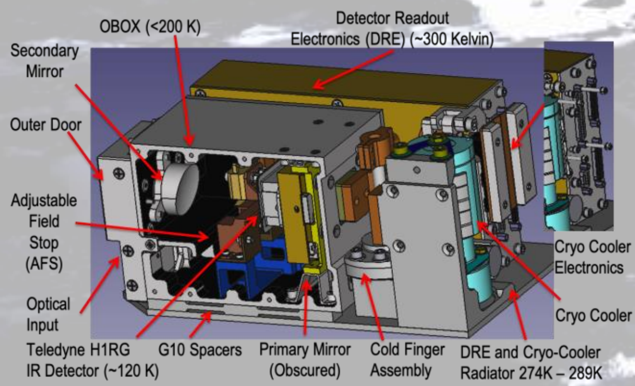
Further Evidence for Water



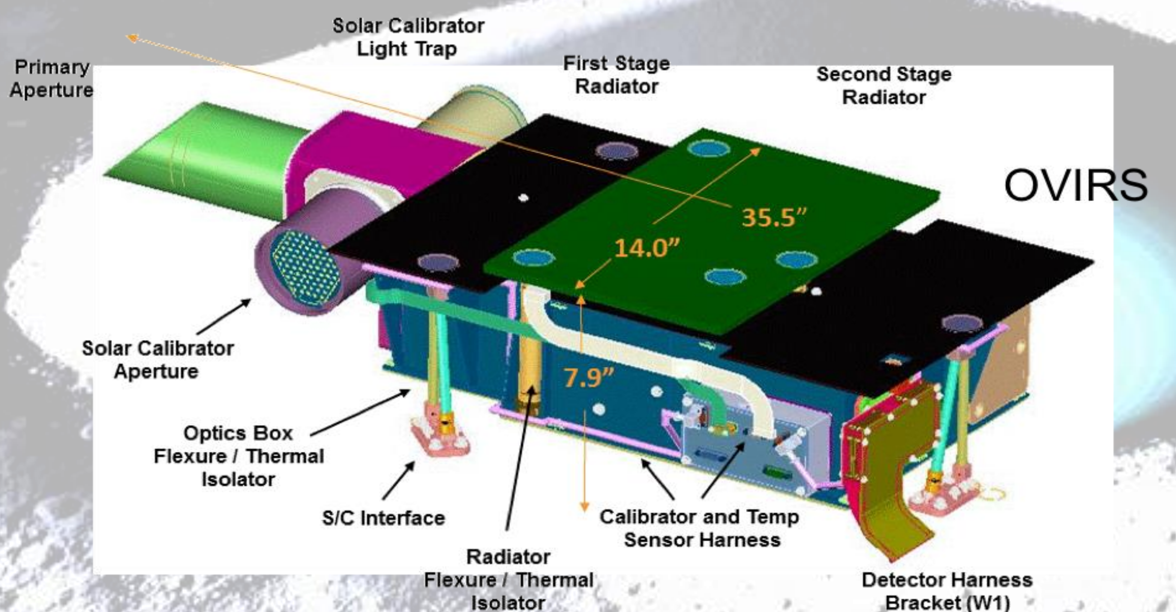
M3 calculated ESPAT estimated water content (Apollo landing sites in yellow) map (A), all longitude-averaged latitude profile (B), and +/- 35 degree latitude-averaged longitude profile (C). Li and Milliken, 2017.



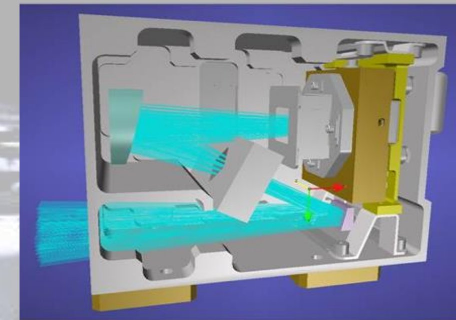
Map of 2.85 u Effective Single Particle Absorption Thickness (ESPAT) derived from M3 at low lunar latitudes. Features apparently associated with pyroclastic deposits, lending credence to hypothesis of volatile-rich (hundreds ppm) sources in mantle. A aristarchus; O orientale, RB Rima Bode, SG Sulpicius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

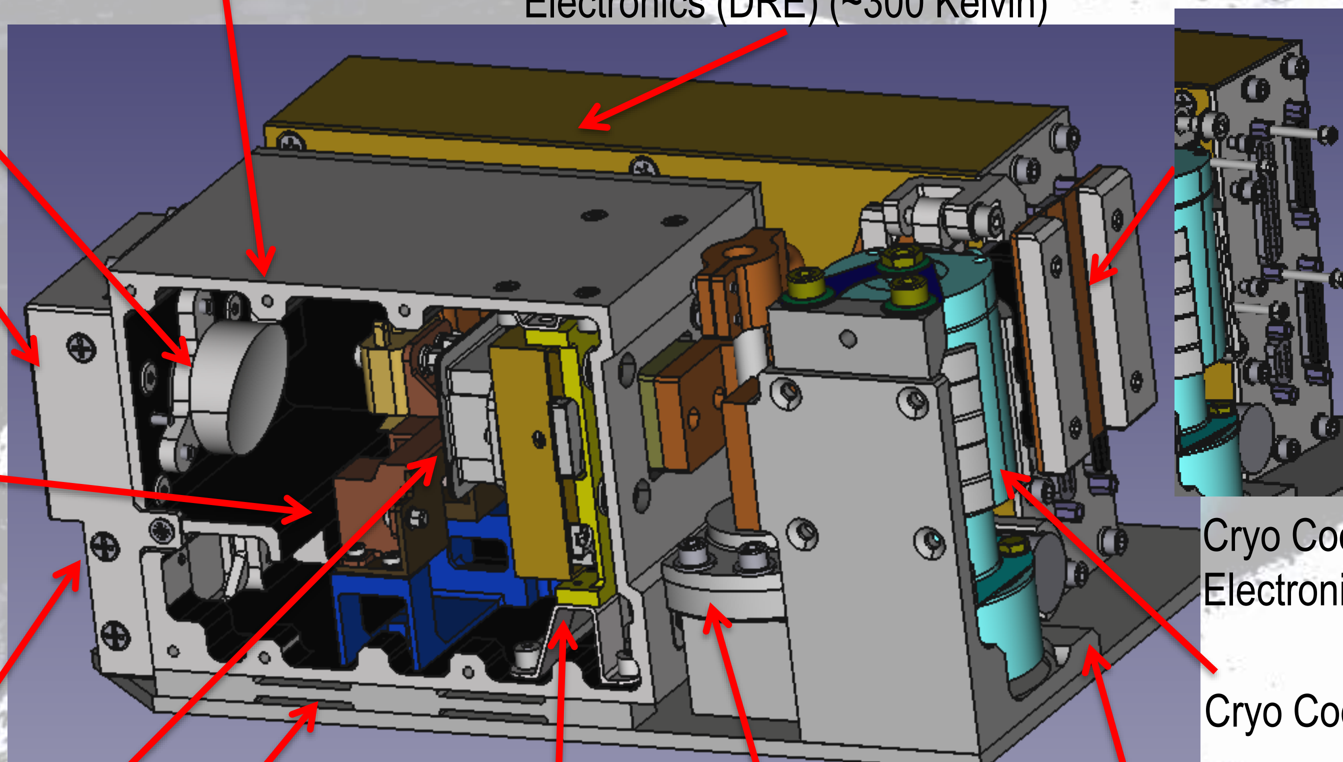


BIRCHES compactness		
Property	OVIRS	BIRCHES
Mass kg	18	3
Power W	10	#15-20 W
Volume U	53 U	2 U
# includes 3 W detector electronics, 1.5 W AFS controller, 10-15 W cryocooler		

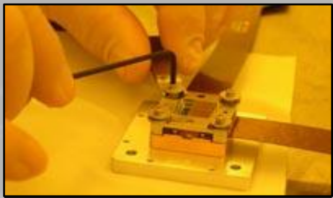


BIRCHES IR Spectrometer HW Architecture

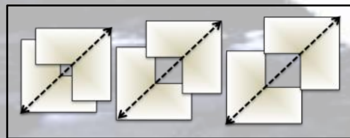




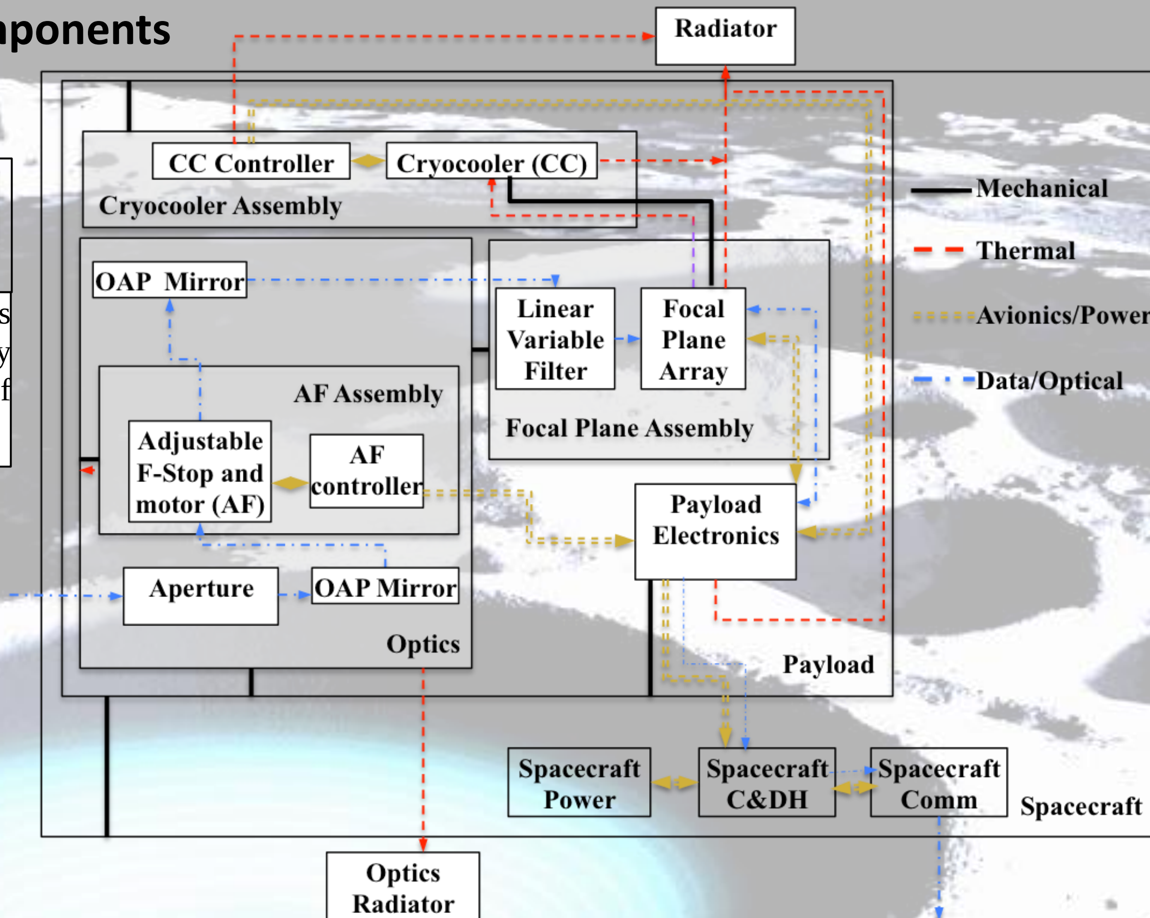
Spectrometer Schematic and Components

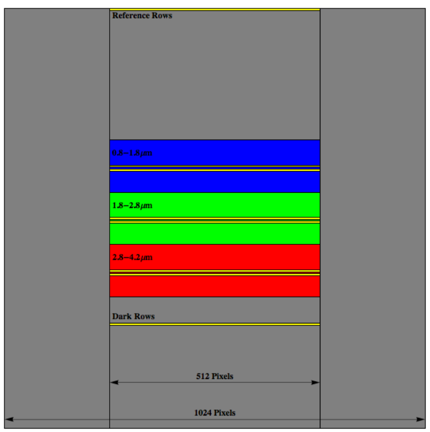


BIRCHES utilizes a compact Teledyne H1RG HgCdTe Focal Plane Array and JDSU linear variable filter leveraging OSIRIS REx OVIRS.



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



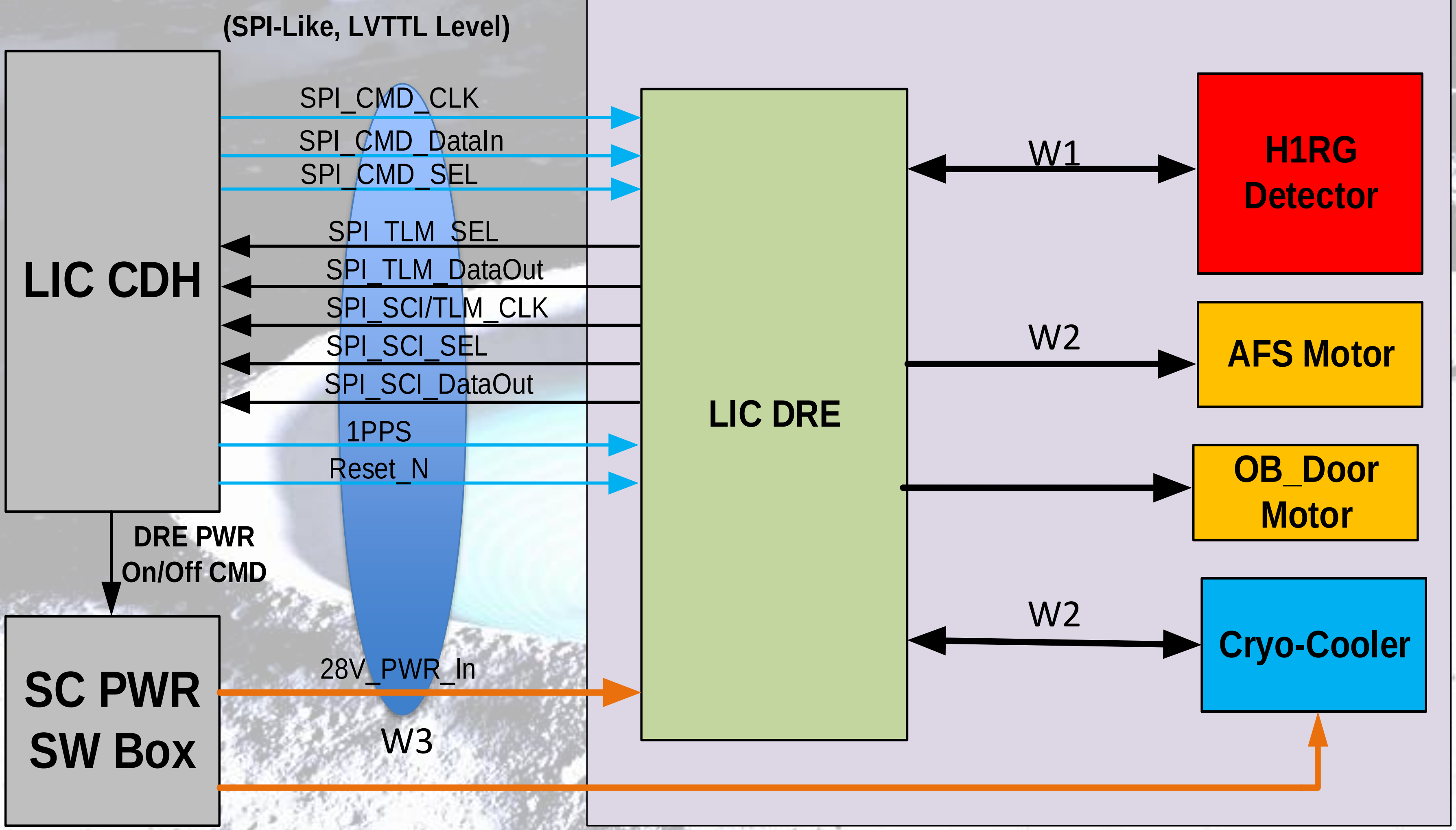


Linear Variable Filter Segments over H1RG focal plane array with reference, dark, segment 1, segment 2, and segment 3 rows (yellow lines) superposed.

BIRCHES Analog Processing Unit (APU) (top)

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

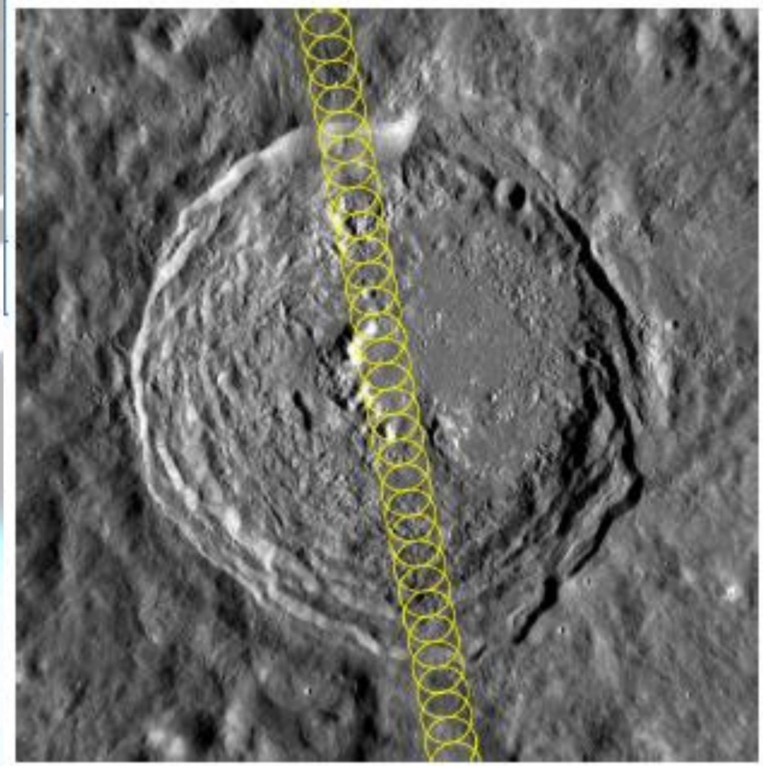
BIRCHES Functional Block Diagram



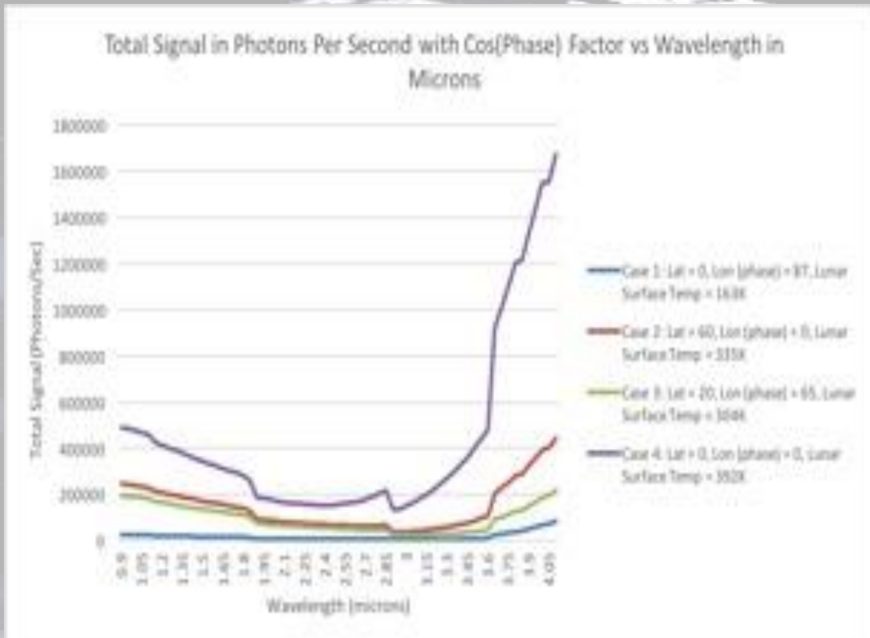
Because of the adjustable field stop, BIRCHES, with its 6 degree FOV, is capable of maintaining at 10 x 10 km footprint over the range of predicted altitudes (100 to 1000 km).

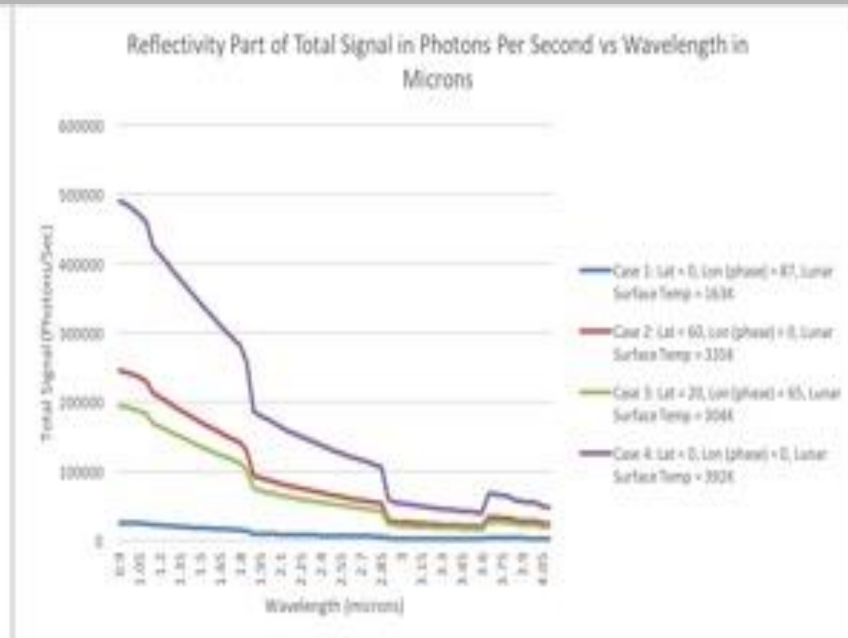
At 100 km altitude, observations, taken every second, are separated by ~2.5 km, allowing alongtrack overlap and oversampling.

Near the poles, the effective SNR is also intrinsically lower, but consecutive orbits overlap. The combination of the adjustable field stop sized to increase the effective FOV and the orbital overlap allow improved statistics through ‘sliding averages’ as well as continuous coverage in an area where water-related features are anticipated to be relatively abundant.



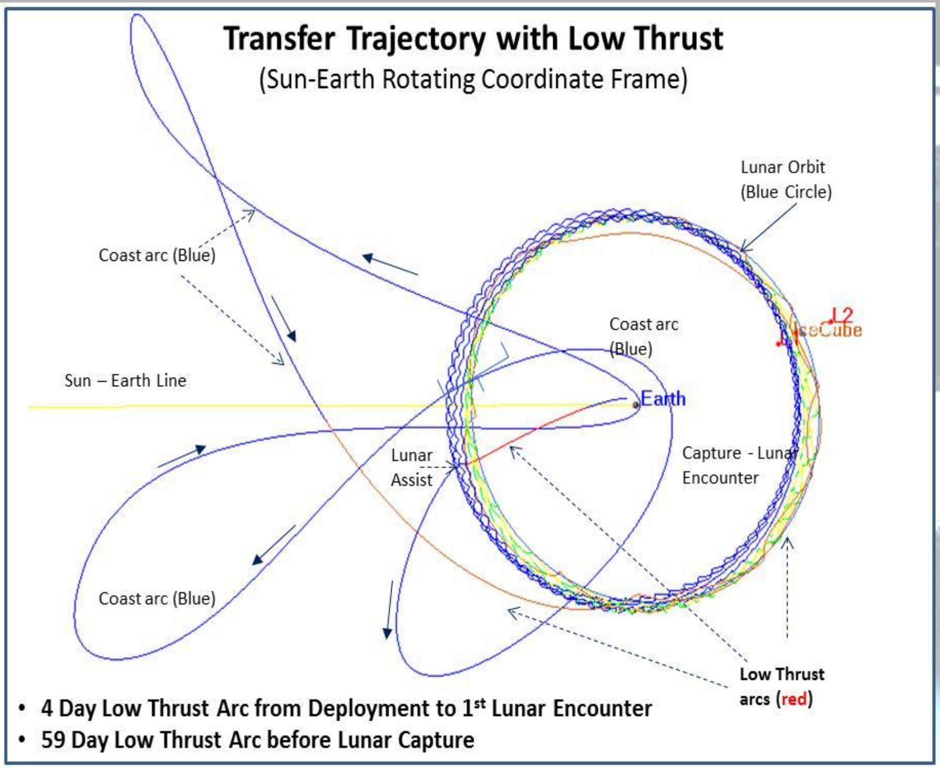
BIRCHES overlapping along-track observations with 10 km footprint maintained by AFS over Vasilov Crater (100 km diameter).



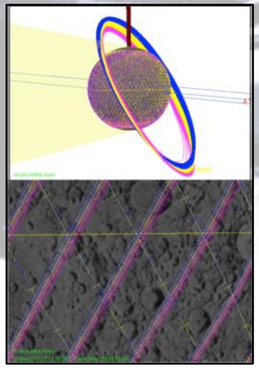


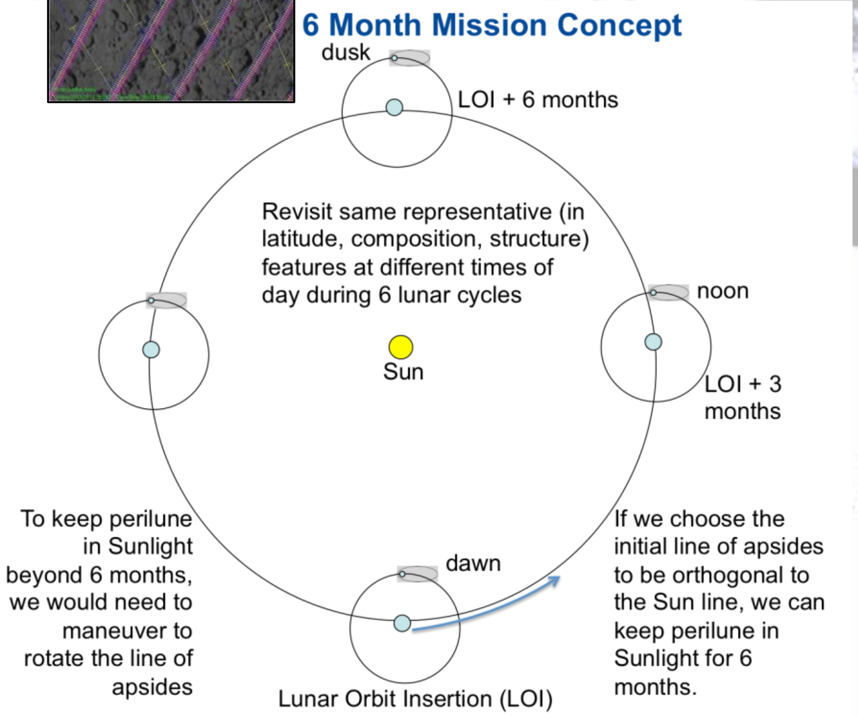
Case	Lat	ToD	Temp K	Reflectivity @ 3um photons/sec	Total Signal	SNR	Band depth/PPM water		
							0.1/1000	0.05/500	0.01/100
1	0	87	163	3254	2760	52	276	138	27
2	60	0	335	39045	26400	162	2640	1320	264
3	20	65	304	24279	20963	145	2096	1480	210
4	0	0	395	150777	52800	230	5280	2640	528

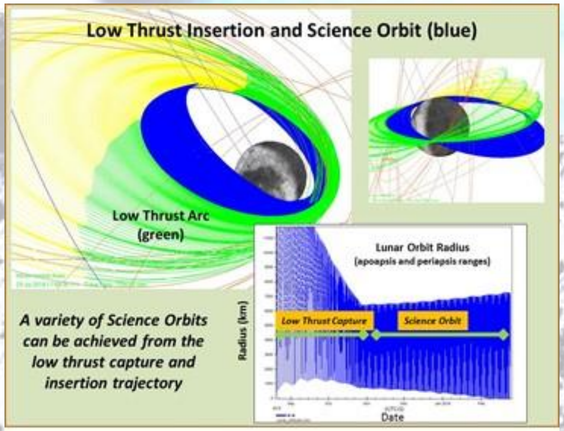
Lunar Ice Cube MIssion Concept



- 4 Day Low Thrust Arc from Deployment to 1st Lunar Encounter
- 59 Day Low Thrust Arc before Lunar Capture







Challenges Summary

Challenges and Mitigations

Thermal design (on-orbit heat removal an issue for 6U, and on-surface heat retention during lunar night an issue if minimum resource (including cost) solutions sought: In future, take advantage of High performance thermal solutions now being developed. Additional work (remove some stand offs, modify detector surfaces, add small dedicated deployable radiator, variable thickness radiator) to reduce heat transfer to detector to reduce pixel saturation without increasing mass.

Development process: version controlled design and interface control documentation, and scheduled essential reviews and deliverables. Learning curve for 'first deep space qualification'. Define 'threshold' early and go to threshold as cost cap issues arise.

Team membership: high turn over and no guaranteed backups for student team. In future, would appoint staff mission operations and ground data system managers.

Dealing with external management with 'Class A+' orientation or 'out of scope' requests: Be prepared to leverage collaborations, identify and scramble for sources of additional funding

Non-scalable (in cost and schedule) development and operation: Support and utilize design, subsystem simulation and driver tools, operating systems, operations facilities, and data delivery pipeline tools already developed or under development for cubesats.

Conclusions

- Lunar Ice Cube is the most operationally complex cubesat to date.
- Lunar Ice Cube goal to provide measurements from which liquid water, ice, OH distribution across the lunar surface can be derived to understand function of time of day (temperature and illumination) at a variety of representative locations.
- Regardless of the degree of overlap with other missions (LunaH-Map and Lunar Ice Cube) 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.
- We are doing what cubesats are supposed to do: creating an innovative and tailored solution with a standard platform.

On to the Moon in 2021!
Join us for LunarCubes Workshop and Interplanetary Small Satellite Conferences next year!

Your challenging payload requirements needed

pamela.e.clark@jpl.nasa.gov