The Lunar Ice Cube Missions

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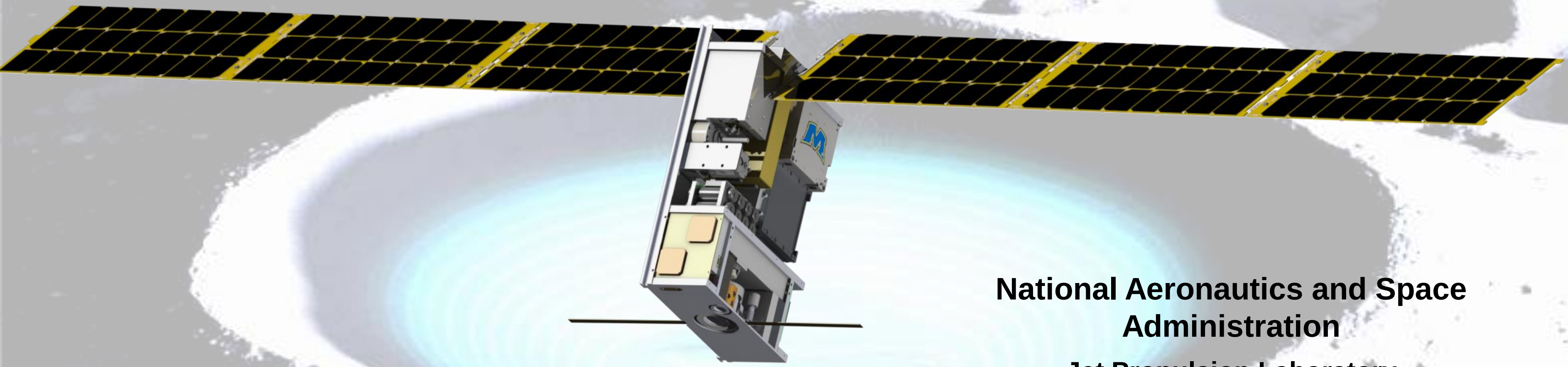


National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Government sponsorship acknowledged.

Jet Propulsion Laboratory
California Institute of Technology

Current Status

EM1 Launch now 2020.

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

For Lunar Ice Cube Science:

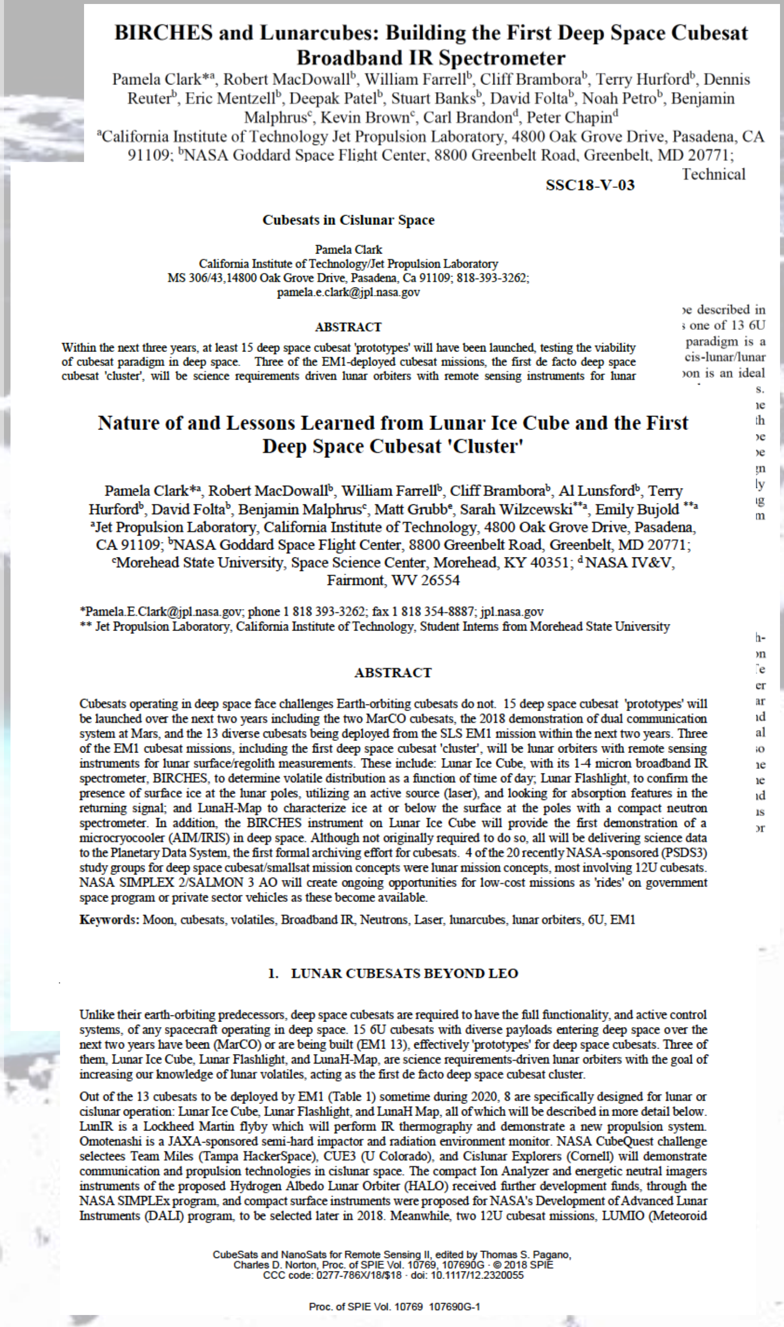
Now completed or in I&T phase for all subsystems

BIRCHES now undergoing optical, digital, and radiometric calibration in simulated environment

FlatSat with emulators testing all subsystems

End to End tests scheduled for summer.

Ready for Data System testing for Level 0 data production this summer. Level 1 data analysis software development will begin this summer.



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

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SSC18-V-03

Cubesats in Cislunar Space

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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

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

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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

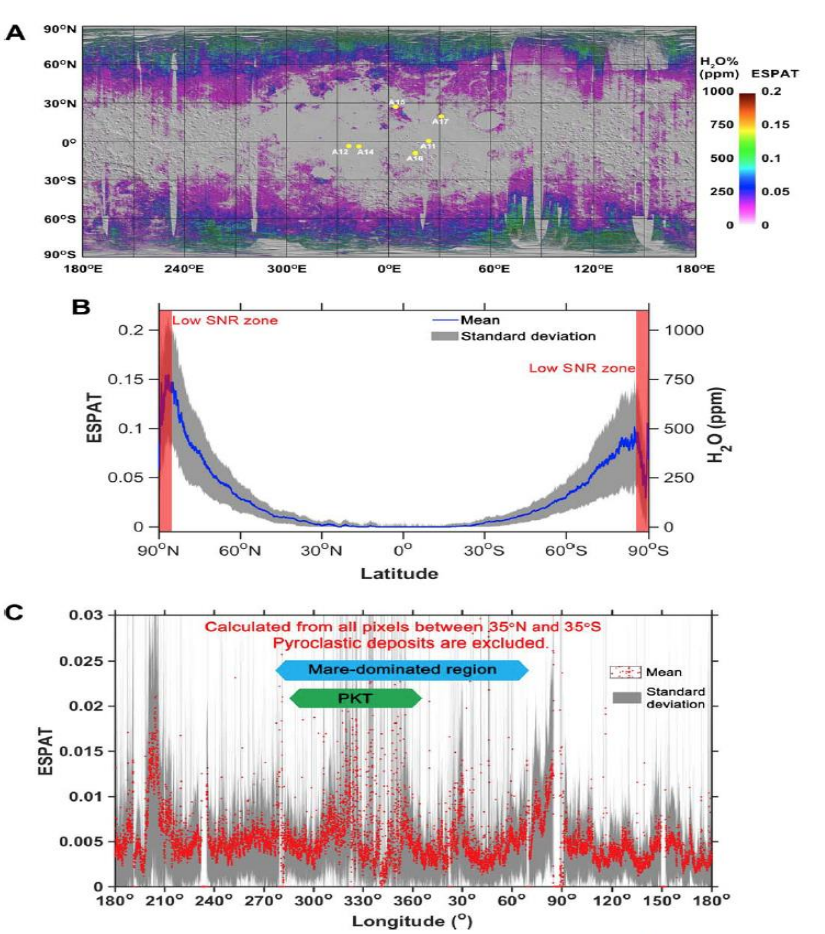
CubeSats and NanoSats for Remote Sensing II, edited by Thomas S. Pagano,
Charles D. Norton, Proc. of SPIE Vol. 10769, 107690G · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2320055

Proc. of SPIE Vol. 10769 107690G-1

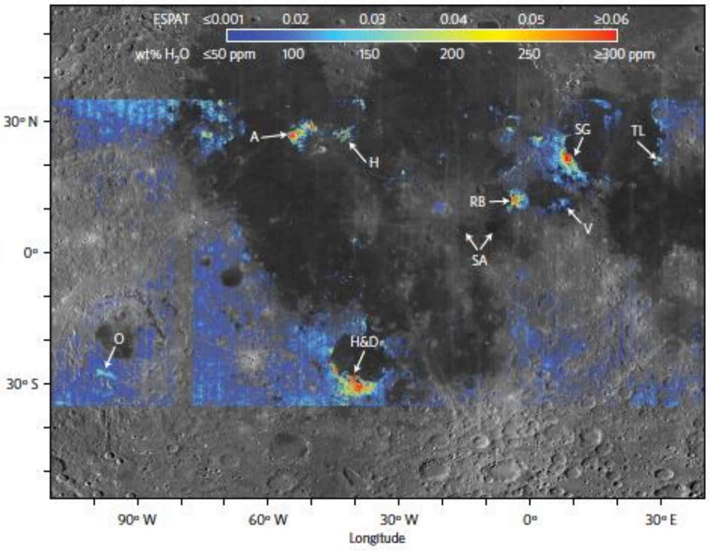
Significance of Water

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.

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.



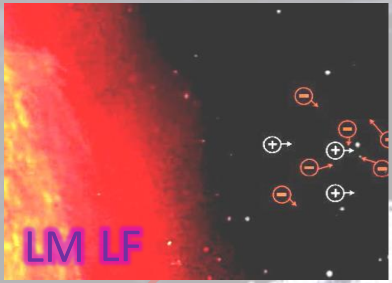
Map of 2.85 u Effective Single Particle Absorption Thickness (ESPAT) derived from M3 at low lunar latitudes. Features apparently associated with pyroclastic deposits, lending credence to hypothesis of volatile-rich (hundreds ppm) sources in mantle. A aristarchus; O orientale, RB Rima Bode, SG Sulpicius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

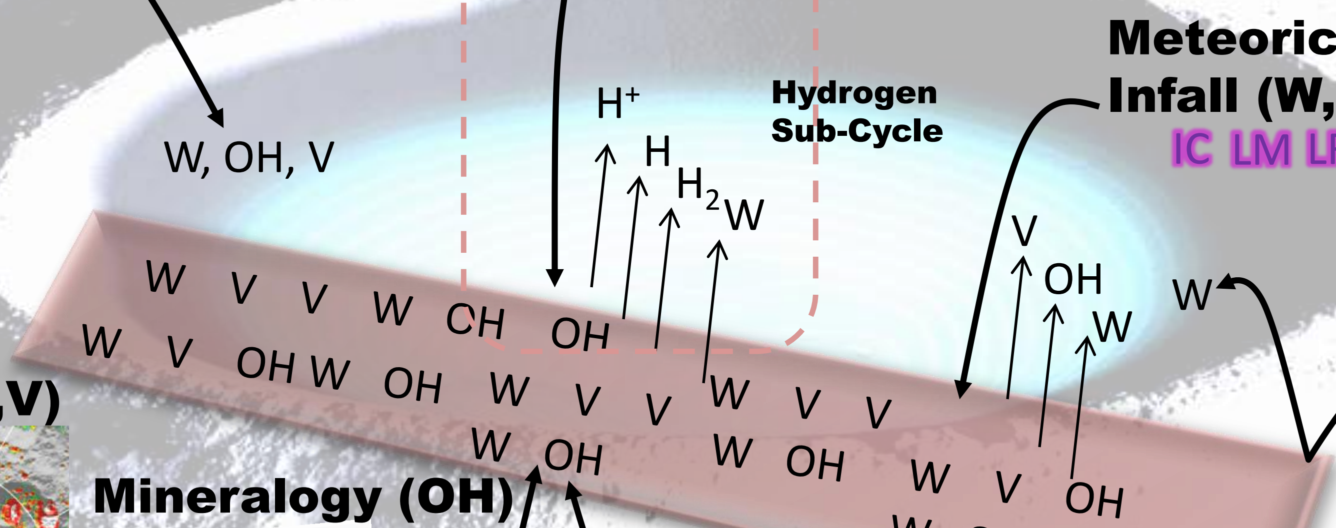
A Lunar Water System

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

W water V volatile S source R remove

IC Lunar Ice Cube LM LunaH-Map LF Lunar Flashlight





Solar Wind (H+)

Hydrogen Sub-Cycle

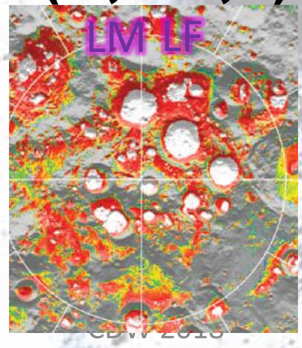
Meteoric Infall (W, OH, V)

IC LM LF

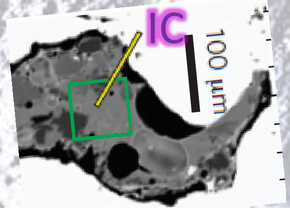
Thermal Migration

IC LM LF

Poles (W, OH,V)



Mineralogy (OH)



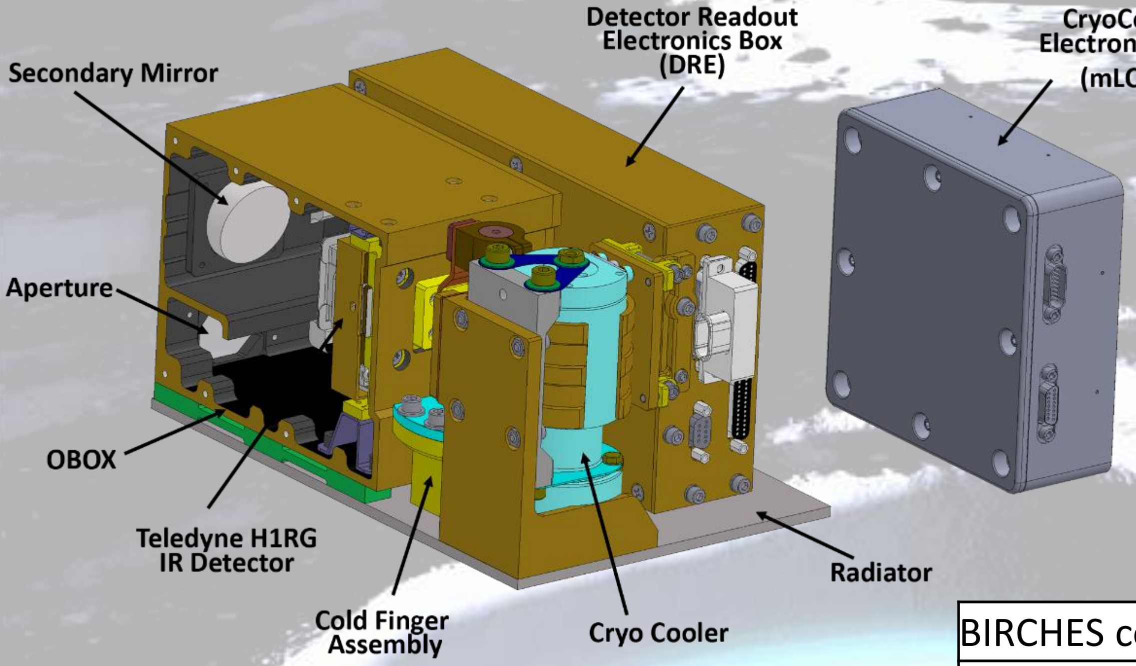
Pyroclastics (Bound H2O)

Modified from Farrell et al, 2017, LEAG

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

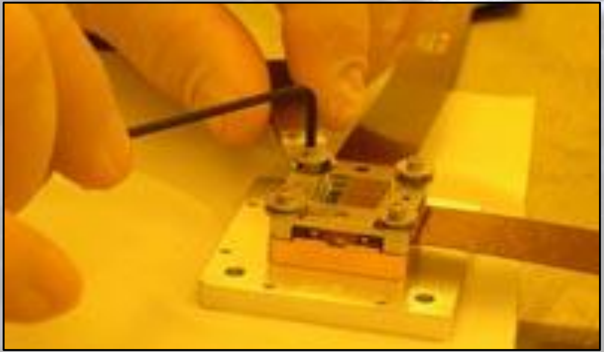


BIRCHES compactness

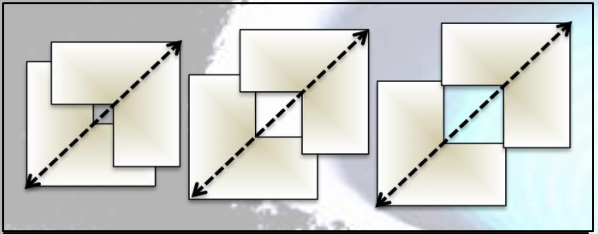
Property	Ralph	BIRCHES
Mass kg	11	3
Power W	5	#10-20 W
Size cm	49 x 40 x 29	10 x 10 x 15

includes 3 W detector electronics, 1.5 W AFS controller, 5-10 W cryocooler

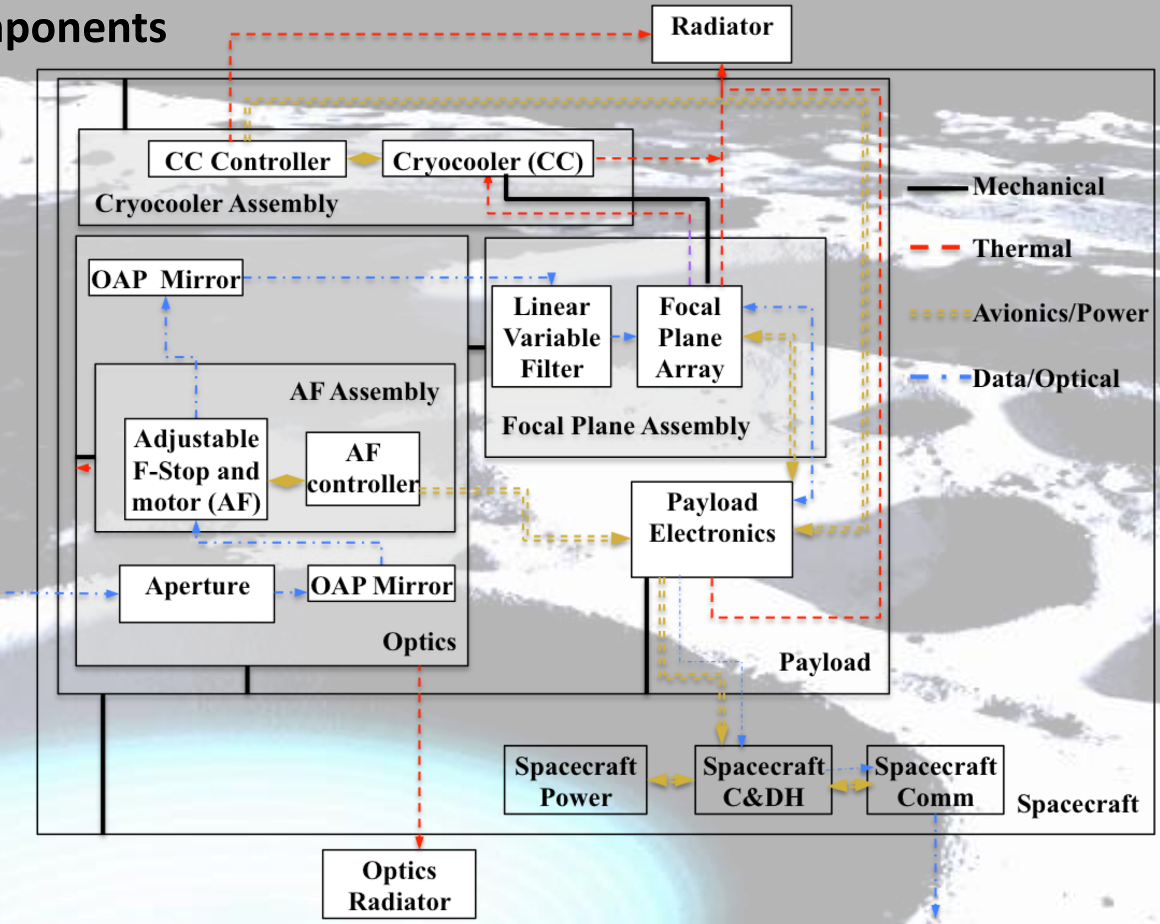
Spectrometer Schematic and Components



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



Radiator

CC Controller

Cryocooler (CC)

Cryocooler Assembly

OAP Mirror

Linear Variable Filter

Focal Plane Array

Focal Plane Assembly

AF Assembly

Adjustable F-Stop and motor (AF)

AF controller

Payload Electronics

Aperture

OAP Mirror

Optics

Payload

Spacecraft Power

Spacecraft C&DH

Spacecraft Comm

Spacecraft

Optics Radiator

Mechanical

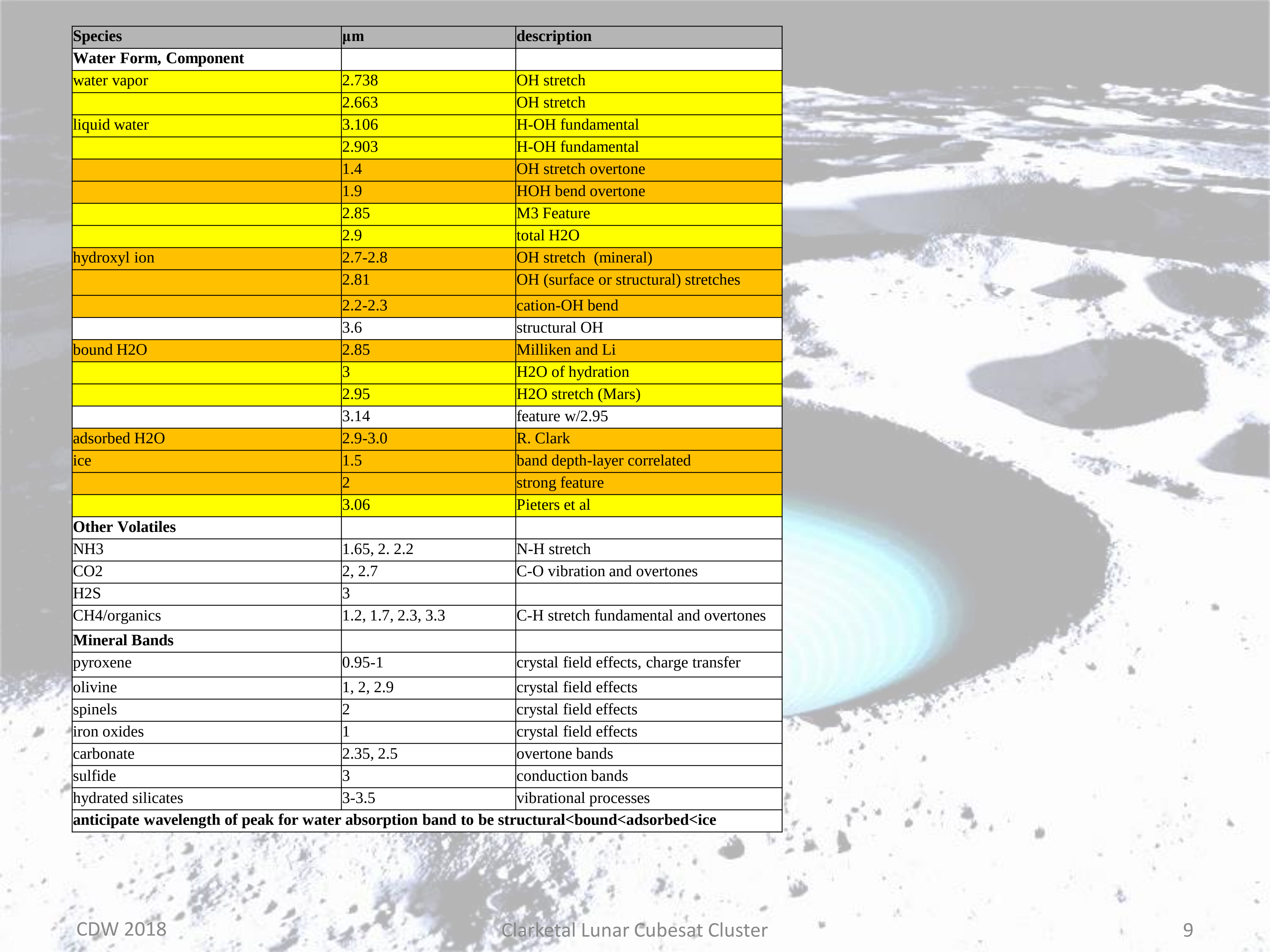
Thermal

Avionics/Power

Data/Optical

BIRCHES Analog Processing Unit (APU) (top)

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



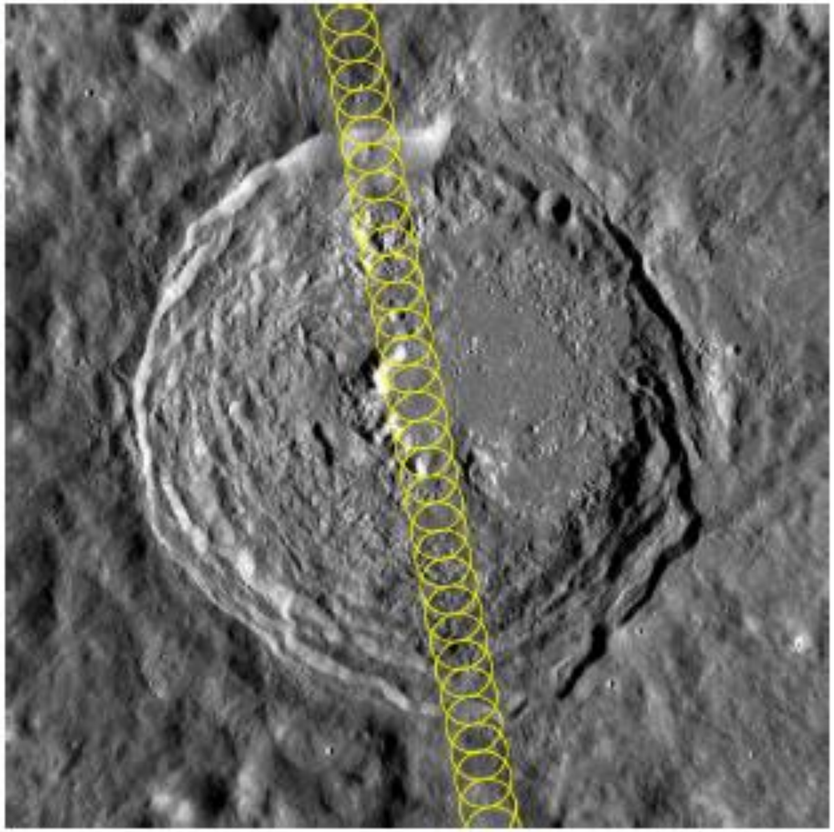
Species	µm	description
Water Form, Component		
water vapor	2.738	OH stretch
	2.663	OH stretch
liquid water	3.106	H-OH fundamental
	2.903	H-OH fundamental
	1.4	OH stretch overtone
	1.9	HOH bend overtone
	2.85	M3 Feature
	2.9	total H_2O
hydroxyl ion	2.7-2.8	OH stretch (mineral)
	2.81	OH (surface or structural) stretches
	2.2-2.3	cation-OH bend
	3.6	structural OH
bound H_2O	2.85	Milliken and Li
	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

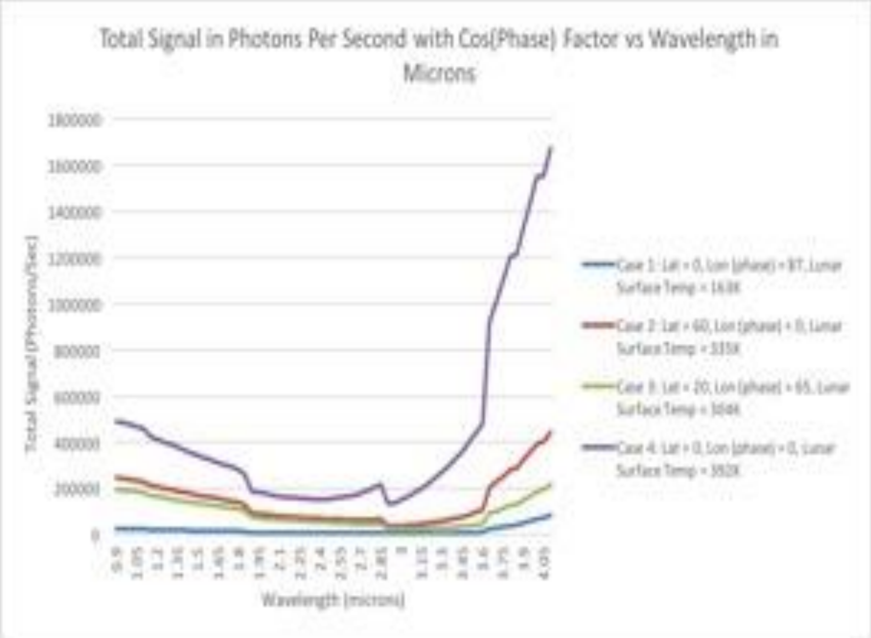
Requirement
A footprint of 10 km from an altitude of 100 km

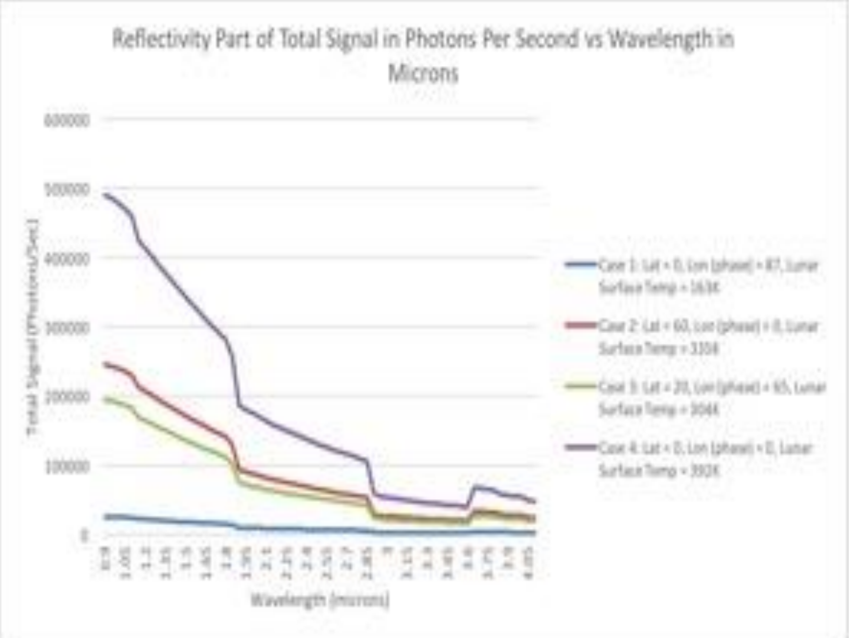
Footprint 10 km in along track direction regardless of altitude, consecutive observations separated by a couple of kilometers; greater overlap of consecutive tracks at poles, separted by a couple of kilometers

- 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)



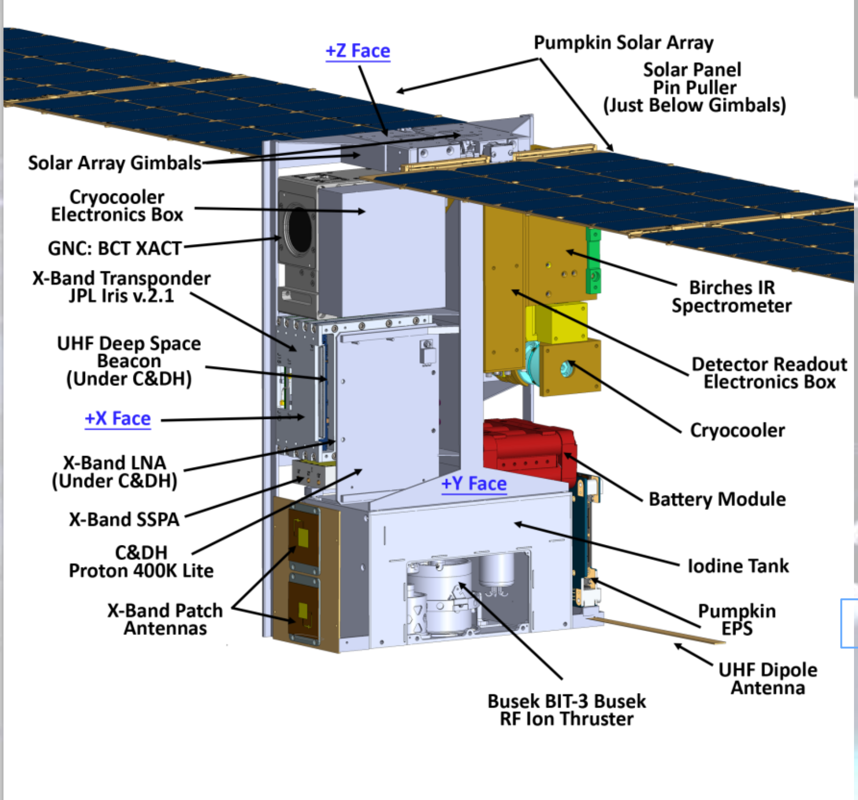
Vavilov Crater:
100 km in diameter
1° S, 138° W

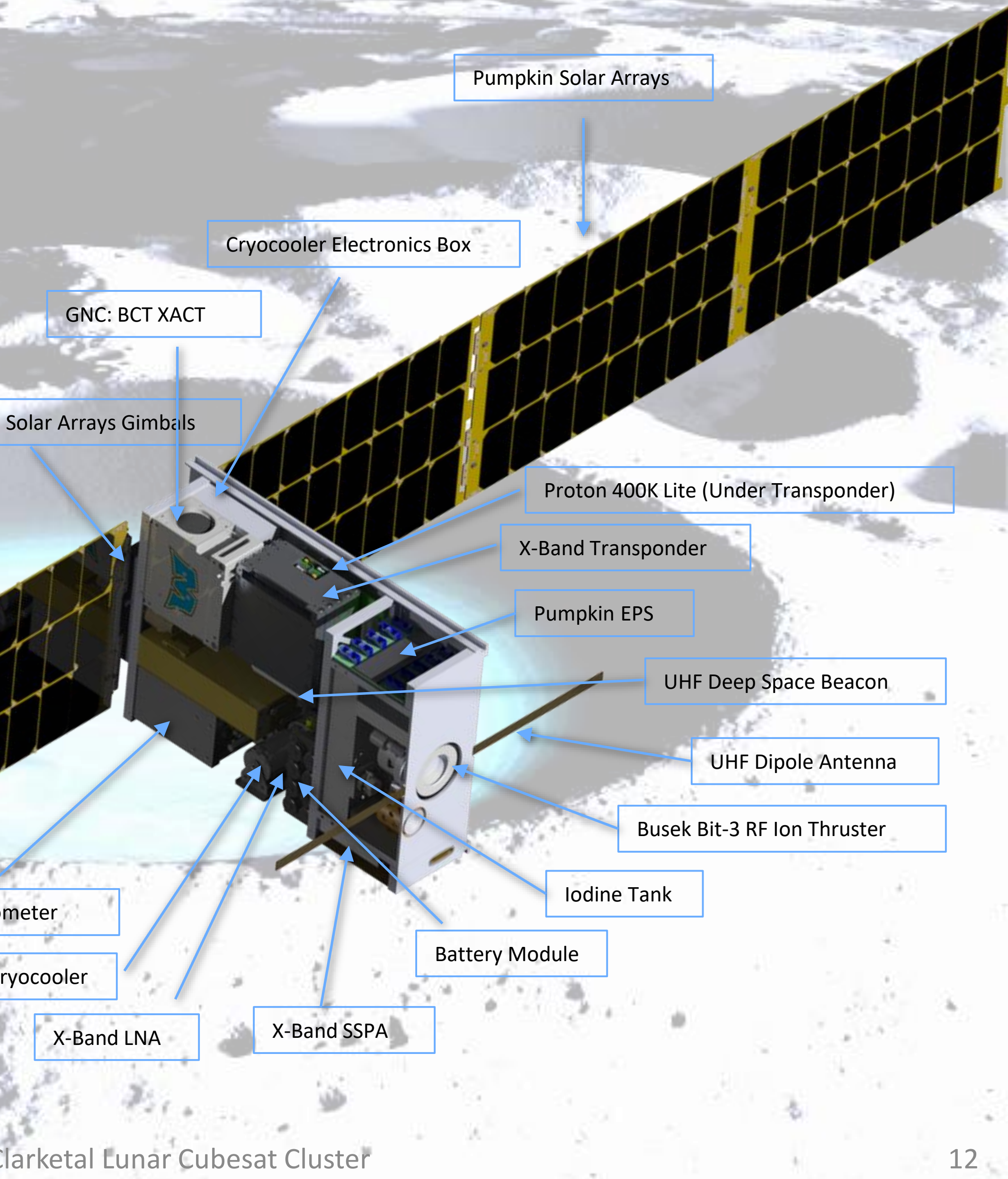

Total Signal in Photons Per Second with Cos(Phase) Factor vs Wavelength in Microns


Reflectivity Part of Total Signal in Photons Per Second vs Wavelength in Microns

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





Pumpkin Solar Arrays

Cryocooler Electronics Box

GNC: BCT XACT

Solar Arrays Gimbals

Proton 400K Lite (Under Transponder)

X-Band Transponder

Pumpkin EPS

UHF Deep Space Beacon

UHF Dipole Antenna

Busek Bit-3 RF Ion Thruster

Iodine Tank

Battery Module

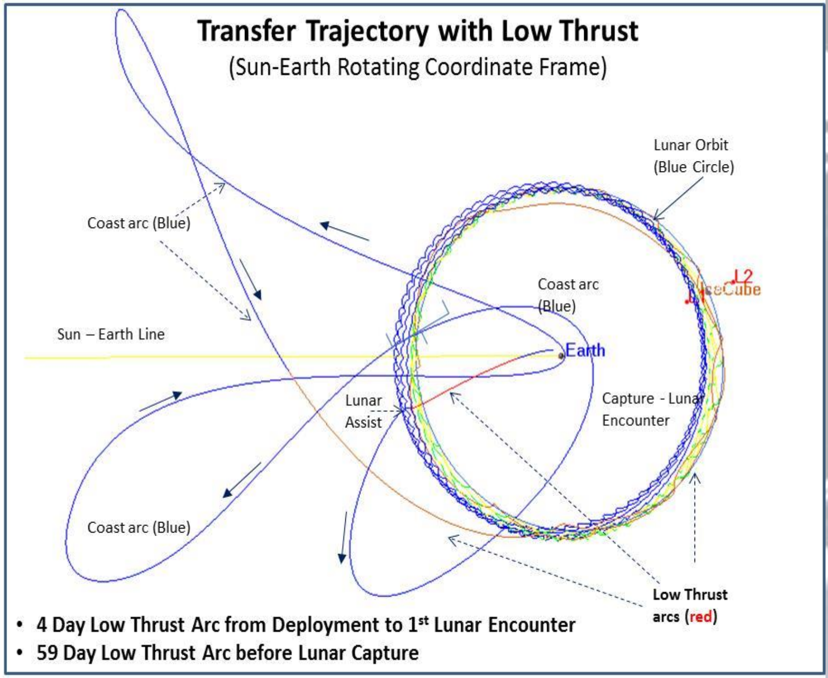
BIRCHES IR Spectrometer

Cryocooler

X-Band LNA

X-Band SSPA

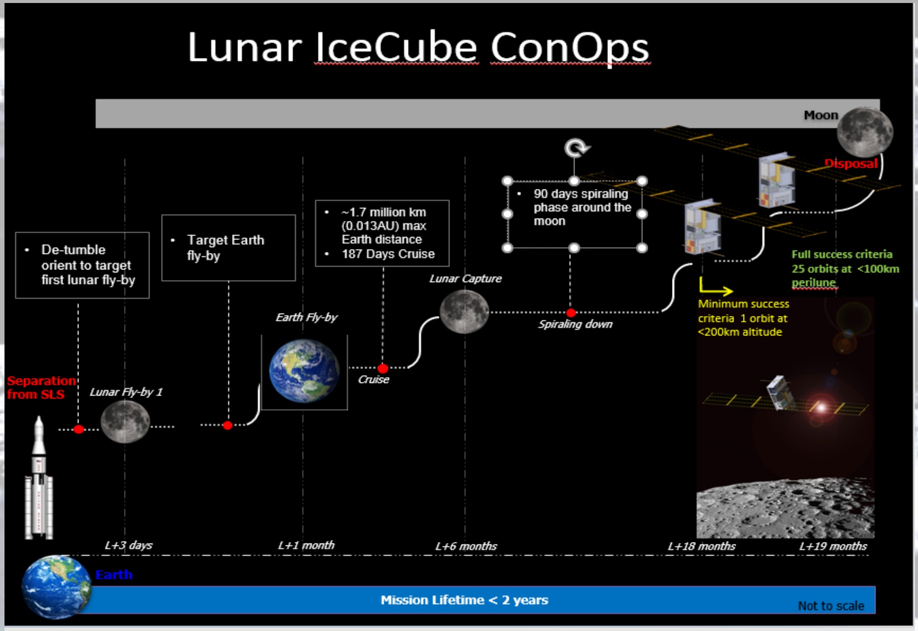
Lunar Ice Cube MIssion Concept



Transfer Trajectory with Low Thrust

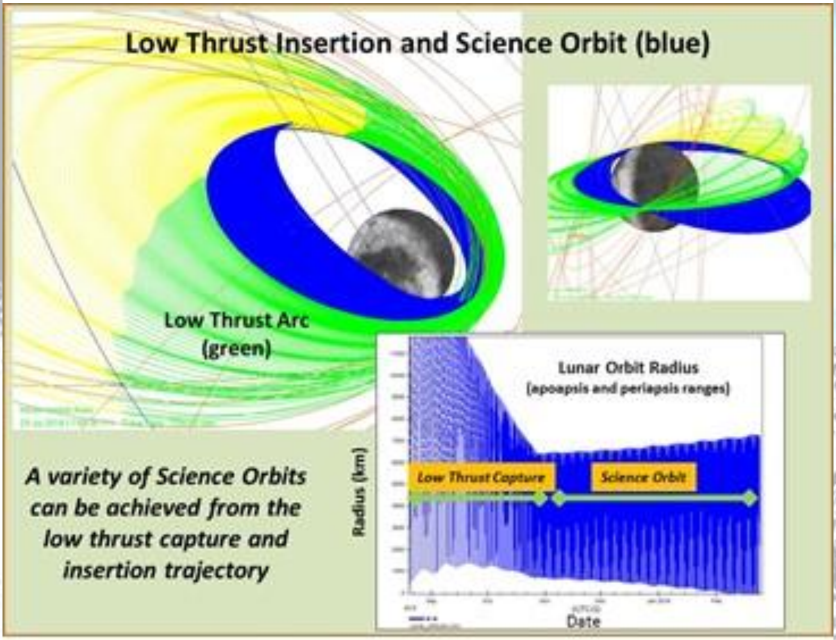
(Sun-Earth Rotating Coordinate Frame)

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



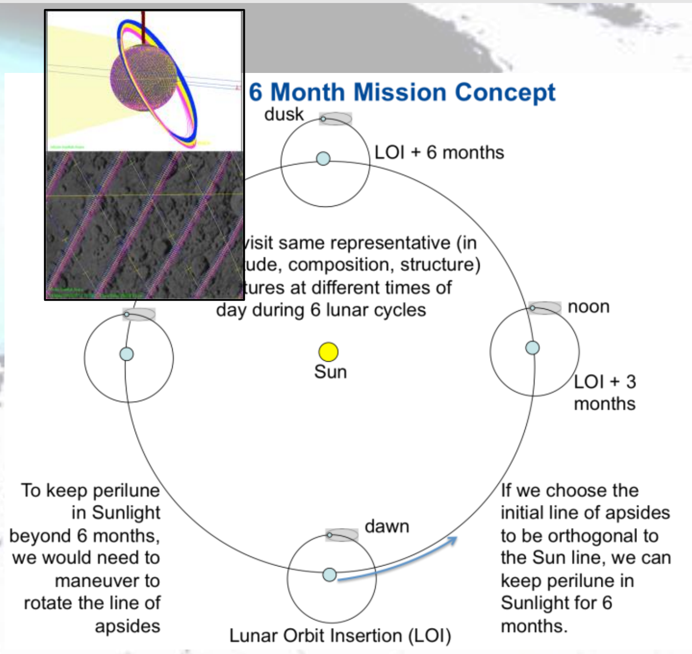
Lunar IceCube ConOps

- De-tumble orient to target first lunar fly-by
- Target Earth fly-by
- ~1.7 million km (0.013AU) max Earth distance
- 187 Days Cruise
- 90 days spiraling phase around the moon



Low Thrust Insertion and Science Orbit (blue)

A variety of Science Orbits can be achieved from the low thrust capture and insertion trajectory



6 Month Mission Concept

isit same representative (in
ude, composition, structure)
tures at different times of
day during 6 lunar cycles

To keep perilune in Sunlight beyond 6 months, we would need to maneuver to rotate the line of apsides

If we choose the initial line of apsides to be orthogonal to the Sun line, we can keep perilune in Sunlight for 6 months.

Planned Lunar Cubesat Payloads

Mission	Goal	Program
Lunar Ice Cube	Orbit, any form or state of water, as function of time of day	NASA HEOMD, EM1
Lunar Flashlight	Orbit, South Pole surface ice in PSRs	NASA HEOMD, EM1
LunaH-Map	Orbit, South Pole, ice on surface to 1 meter depth	NASA/SMD, EM1
LunIR	flyby, lunar regolith properties	NASA HEOMD, EM1
Omotenashi	impactor, radiation	JAXA (on EM1)
Team Miles	CubeQuest, demonstrate propulsion and communication milestones	NASA STMD, EM1
CUE3	CubeQuest, demonstrate propulsion and communication milestones	NASA STMD, EM1
Cislunar Explorers	CubeQuest , demonstrate propulsion and communication milestones	NASA STMD, EM1
LUMIO	L2 orbit, camera, meteoroids impacting Moon from L2	ESA LUCE
VMMO	Orbit, Shackleton, volatiles, radiation	ESA LUCE

Proposed NASA Lunar Smallsat/Cubesat Payloads

Mission	Goal
CLPS	Small Payloads for Commercial Lunar Landers, starting in 2020
Polar Mobile	NASA instrumented Rover 2024. Rover-mounted Payload opportunities TBD
Human Landing	Return to the Moon 2025. Handheld instrument opportunities TBD

Challenges Summary

Challenges and Mitigations

Payload Requirements Flow down process: Realization of the need for meshing of Maker and Aerospace Engineering cultures in a way that allows trace back to payload-driven mission goals, has version controlled design and interface control documentation, and scheduled essential reviews and deliverables, and yet maintains flexibility. Learning curve for 'first deep space qualification'. Define 'threshold' early and go to threshold as cost cap issues arise.

team membership: Project can work with student team provided 1) experienced leadership with systems orientation as well as 'fixers', and 2) 'deputies' for major roles to cope with high turn over.

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

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: Take advantage of High performance thermal solutions now being developed.

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.

Large uncertainties in available Infrastructure (transportation and communication): More reasonable options should be evolving now.

Conclusions

- Lunar Ice Cube is the most operationally complex cubesat to date.
- 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 three or more lunar cycles for pole to pole swaths of the lunar surface to provide a basis for understanding global water dynamics.
- 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.
- We are doing what cubesats are supposed to do: creating an innovative and tailored solution with a standard platform.

On to the Moon in 2020!
Join us for LunarCubes Workshop and Interplanetary Small Satellite Conferences next year!

Your challenging payload requirements needed

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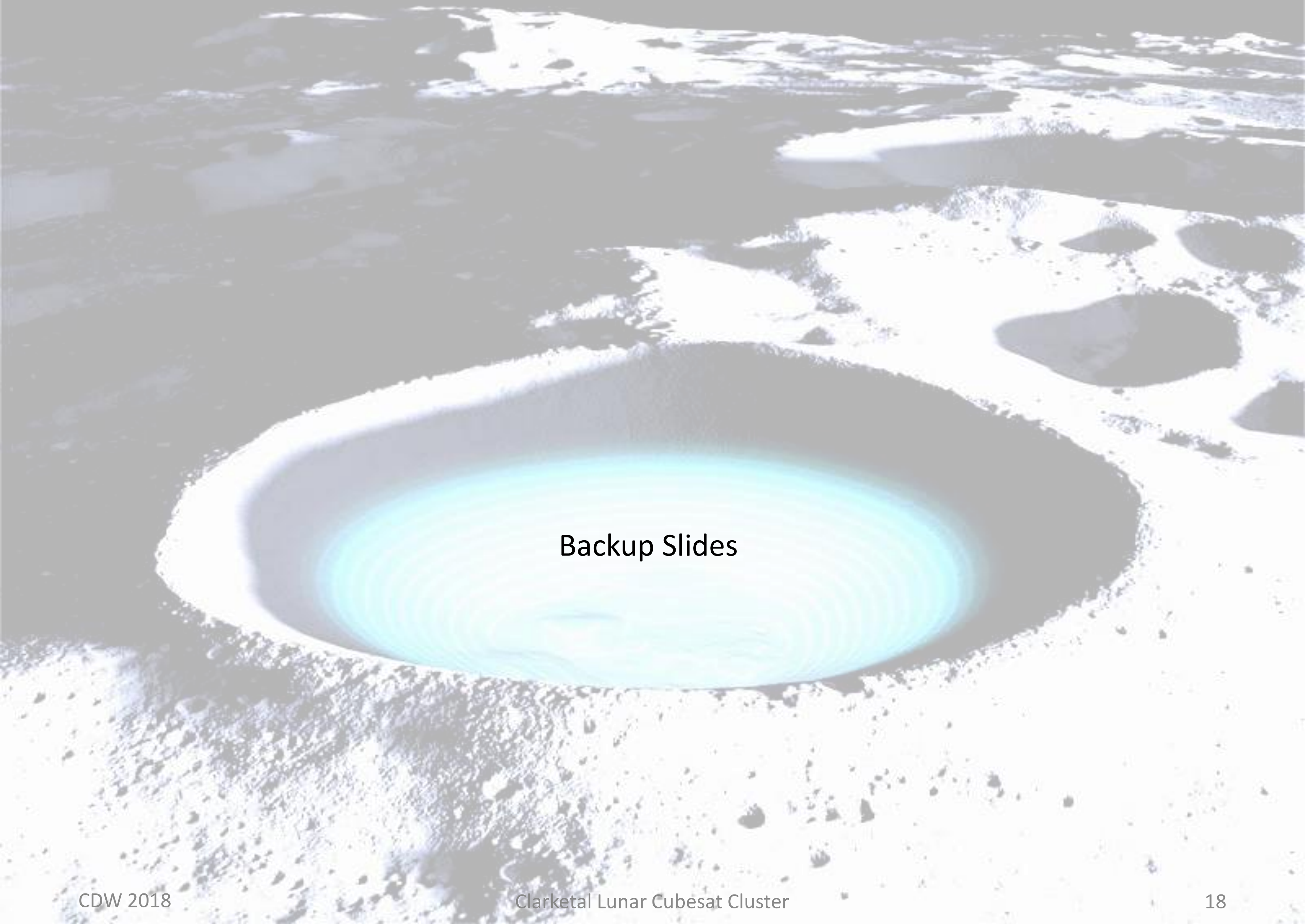
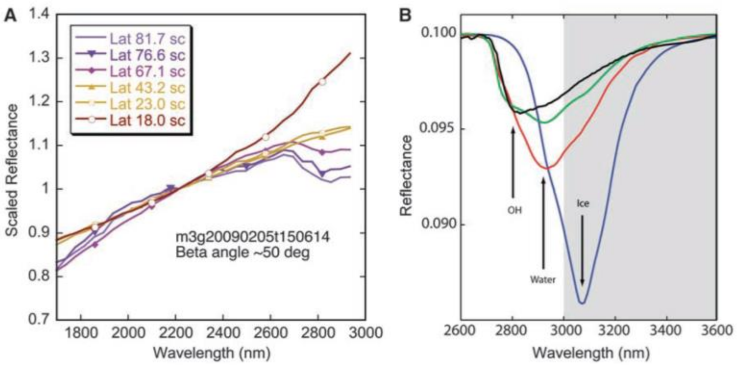
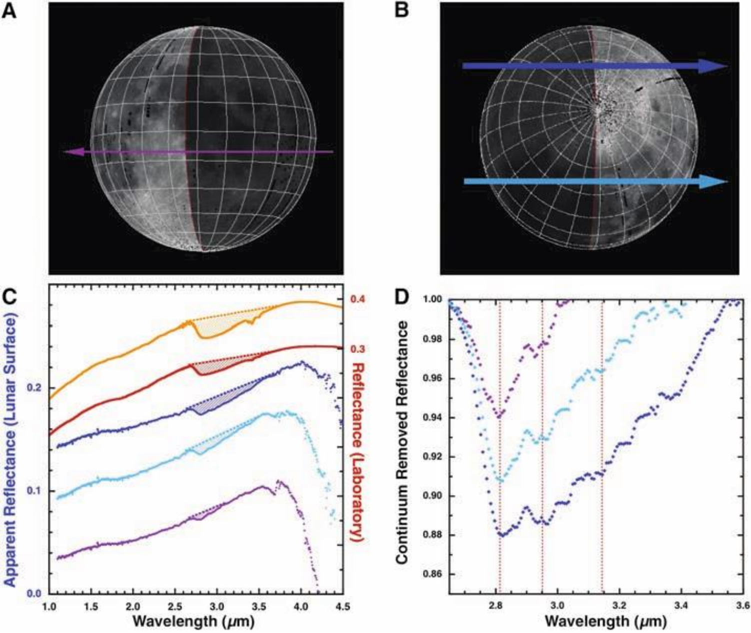


Backup Slides

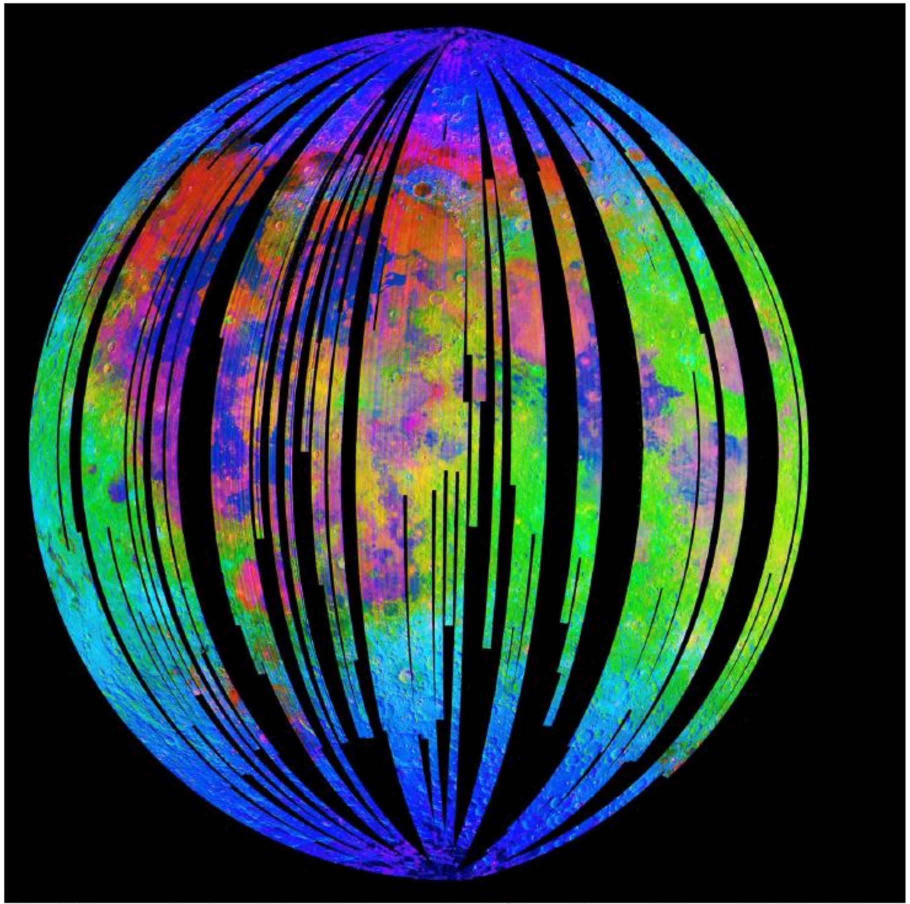
Evidence for Water



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

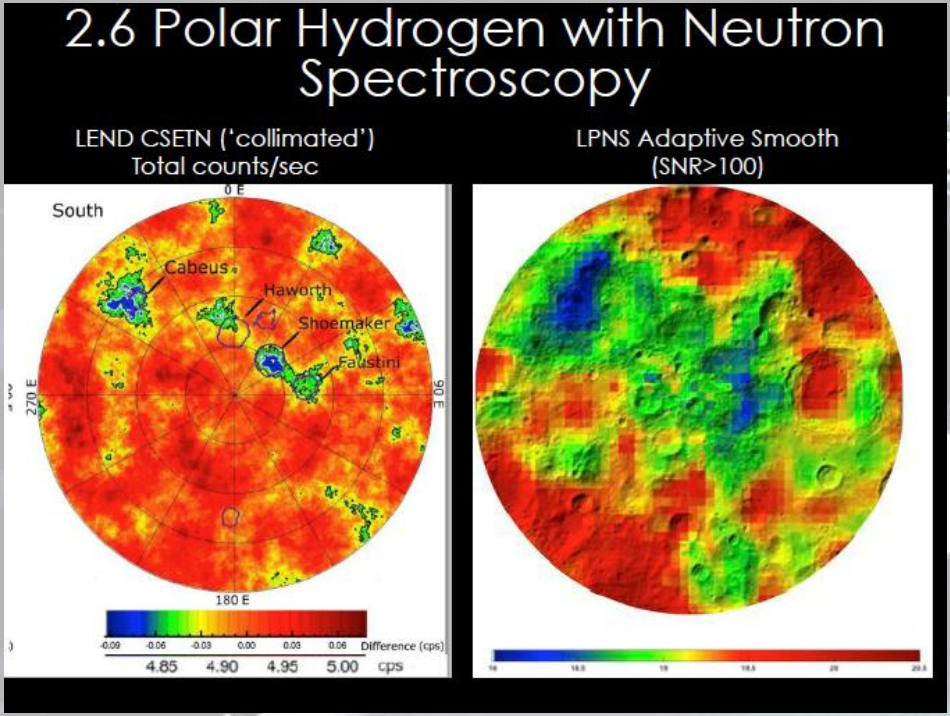


Reflectance spectra with absorption feature strength correlated with time of day. Deep Impact Epoxi. Sunshine et al 2009



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



2.6 Polar Hydrogen with Neutron Spectroscopy

LEND CSETN ('collimated')
Total counts/sec

LPNS Adaptive Smooth
(SNR>100)

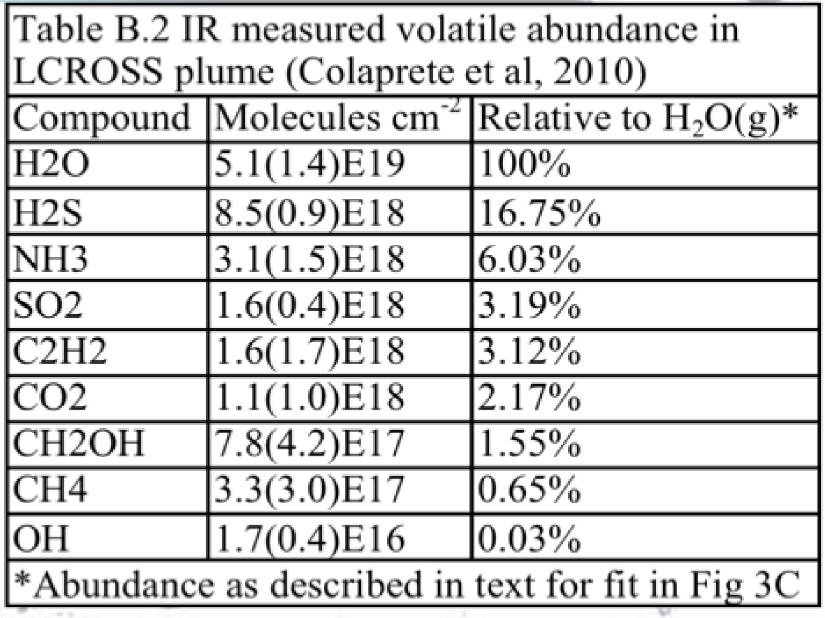


Table B.2 IR measured volatile abundance in LCROSS plume (Colaprete et al, 2010)

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