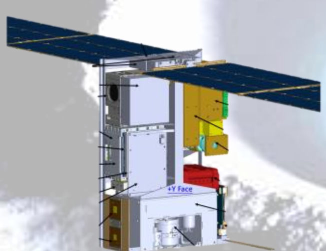
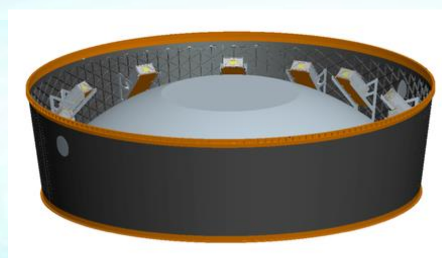
Broadband InfraRed Compact High-resolution Exploration Spectrometer: Lunar Volatile Dynamics for the Lunar Ice Cube Mission

CalTech/Jet Propulsion Laboratory: **P.E. Clark (**Science PI); Kris Angkasa;
Morehead State University, PI, Bus, Ground Communication, Mission Operations:
B. Malphrus (PI), B. Twiggs, Jeff Kruth, Kevin Brown, M. Coombs, E. Thomas,
Graduate and Undergraduate Students;
NASA/GSFC Payload: C. Brambora, T. Hurford, R. MacDowall, D. Reuter, W. Farrell, D. Patel, S. Banks, E. Mentzell, R. Manriquez;
NASA/GSFC Flight Dynamics: D. Folta;
Busek Propulsion: M. Tsay, J. Frongillo, J. Model;
Vermont Technical College Software: C. Brandon, P. Chapin, Graduate Students





EM1 Deployment System
for the 'lucky 13'

Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Government sponsorship acknowledged.

Current Status

Team has just had CDR.

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

FlatSat with non rad-hard subsystems and emulators is in development and expected to be in use by later in summer

Trajectory, navigation, and thermal models along with communications links, mass, volume and power budgets evolving and achieving convergence

Development and testing Data System beginning

A SPIE Optics paper with emphasis on BIRCHES has been published

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.

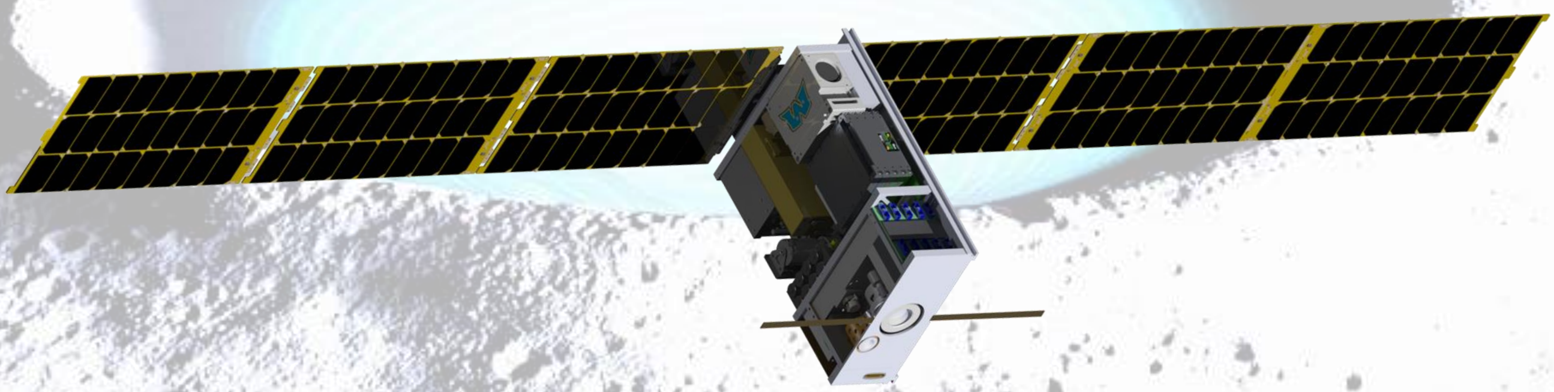
CubeSats and NanoSats for Remote Sensing, edited by Thomas S. Pagano, Proc. of SPIE Vol. 9978, 99780C · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2238332

Lunar Ice Cube Science Goals

Goals	Measurements	HEOMD SKG	Current Context
Primary: Determine distribution of forms and components of water as a function of time of day as an isolated variable. Provide inputs to constrain models for water origin, production, and loss Secondary: Consider impact of latitude, slope, and slope orientation (typical illumination and temperature range), as well as composition and age (additional impact on space weaterhing) on distribution of forms and components of water to the extent possible Tertiary: Determine distribution of other volatiles (e.g., NH_3, H_2S, CO_2, CH_4) to extent possible Tertiary: Consider impact of solar variations if opportunities.	IR measurements in the 1 to 4 micron region associated with volatiles, especially focused on, though not limited to, the 3 micron region at </= 10 nm spectral resolution. Utilize existing datasets from other missions (including LRO, Lunar Prospector, LCROSS, LADEE) to correlate with other parameters listed under goals.	**1-D Polar Resources 7**: Temporal Variability and Movement Dynamics of Surface-Correlated OH and H_2O deposits toward PSR retention **1-D Polar Resources 6**: Composition, Form and Distribution of Polar Volatiles **1-C Regolith 2**: Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith (depending on the final inclination of the Lunar IceCube orbit)	More evidence for surface ice near south pole and solar exposure related effects

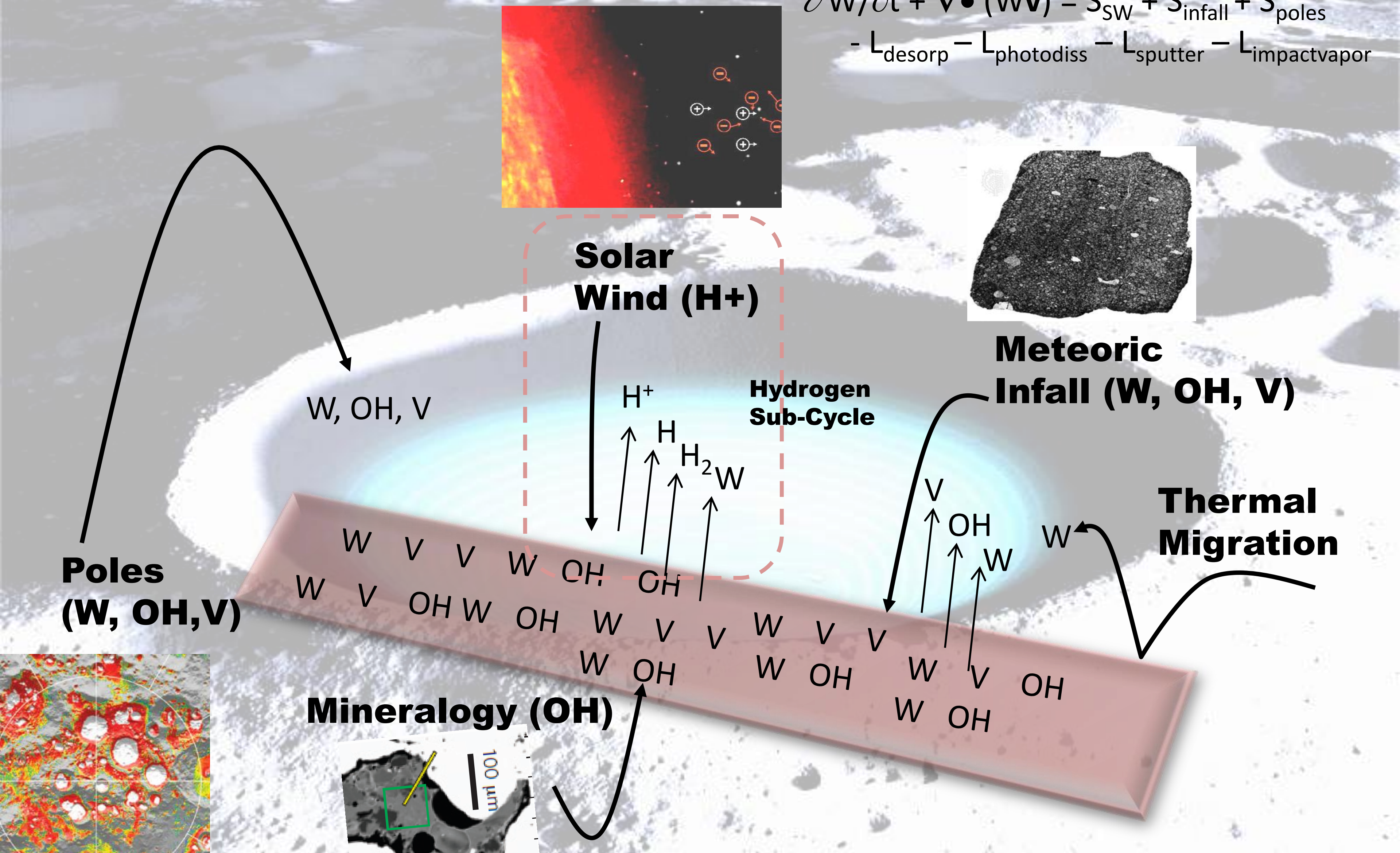
Technology Goals
Demonstrate Enabling Technologies for Interplanetary Cubesats

- **Busek BIT 3** - High isp RF Ion Engine
- **NASA GSFC - BIRCHES** Miniaturized IR Spectrometer - characterize water and other volatiles with high spectral resolution (5 nm) and wavelength range (1 to 4 µm)
- **Space Micro C&DH-** Inexpensive Radiation-tolerant Subsystem
- **JPL Iris v. 2.1** Ranging Transceiver
- **BCT- XACT** ADCS w/ Star Tracker and Reaction Wheels
- **Custom Pumpkin**- High Power (120W) CubeSat Solar Array



New View: A Lunar Water System From Bill Farrell

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



More recent studies and Bottom Line:

- Given BIRCHES measurements indicating variations in liquid water, ice, OH distribution across the lunar surface as function of time of day, ergo, temperature and illumination regime
- Given context of previous observations and ongoing studies
- we can examine water, ice, and OH 'signatures' and implications for water-related processes including hydroxylation, water adsorption or desorption for:
  - Latitude and local magnetic anomalies
  - Local Slope orientation and shadowing
  - Composition, soil type, and maturity
  - Crater size and age
  - Transient (as opposed to systematic) effects such as impact or enhanced solar activity events

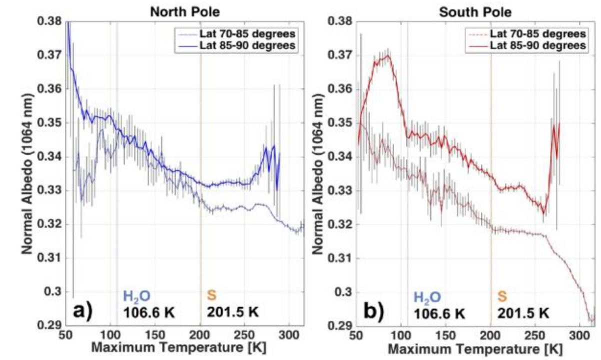


Fig. 5. Average 1064 nm reflectance as a function of maximum temperature (maximum temperature bin width = 3 K) for low slope (slope < 10°) areas free of mass wasting influence for areas within 5° of each pole, and between 5 and 20° from each pole, illustrating spatial heterogeneity in polar reflectance-temperature relationships. **a)** North polar data; **b)** South polar data. Curves plotted with 2σ standard error of the mean. Volatility thresholds for elemental sulfur and water ice are included for comparison. Thresholds were derived by Zhang and Paige (2009) a sublimation rate of 1 mm/Gyr.

Evidence for surface ice at South Pole from LRO LA (Fisher et al 2017) and for magnetic anomaly and latitudinal impacts on space weather 'darkening' (Hemingway at el 2015)

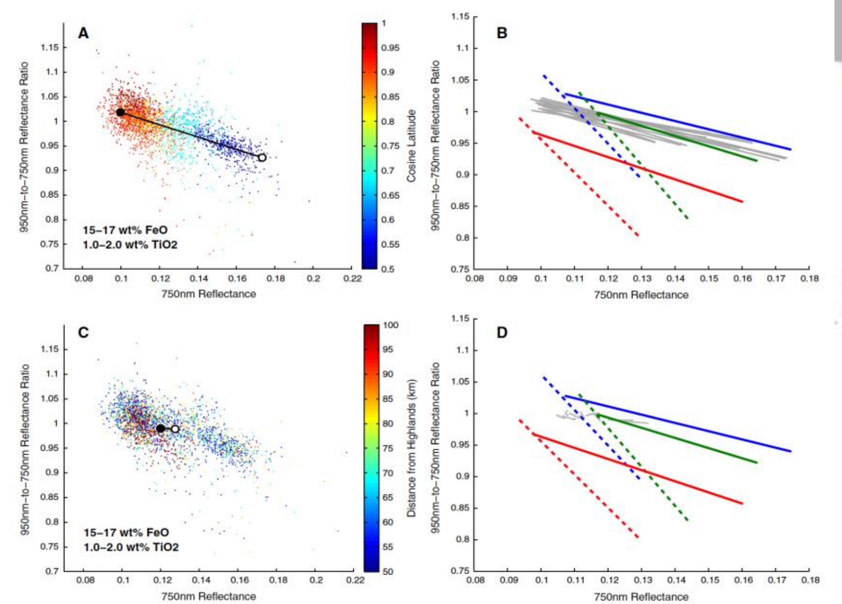
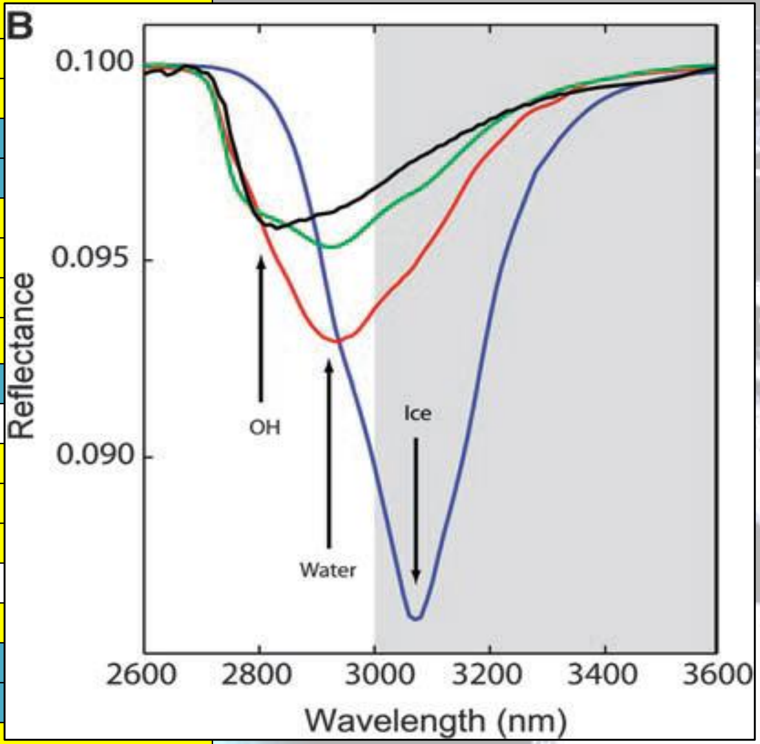


Fig. 15. Color variation of mare surfaces that are at least 50 km from the nearest highlands (compare with Fig. 4, which characterizes the entire lunar surface, and Fig. 10, which characterizes all of the maria). (A) Spectral characteristics of pixels sampled from regions with between 15 and 17 wt% FeO and between 1 and 2 wt% TiO_2. Points are color-coded according to cosine latitude, as in Fig. 4. (B) Compilation of latitudinal trends across the 13 compositional bins compared to the swirl- and impact-related trends (red, green, and blue lines). (C) Spectral characteristics of the same pixels as in (A), except that points are color-coded according to distance from the highlands: blue points correspond to locations that are 50 km from the mare/highland boundary whereas red points correspond to locations that are 100 km or more from the nearest highlands (pixels within 50 km of the nearest highlands are excluded). The black trend line represents a least squares best fit through the data points with the end points indicating the color predicted by the best-fit line at locations 50 km (white circle) and 100 km (black circle) from the mare/highland boundary. (D) Compilation of the 13 highland-distance trend lines (gray lines) compared to the swirl- and impact-related trends (red, green, and blue lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

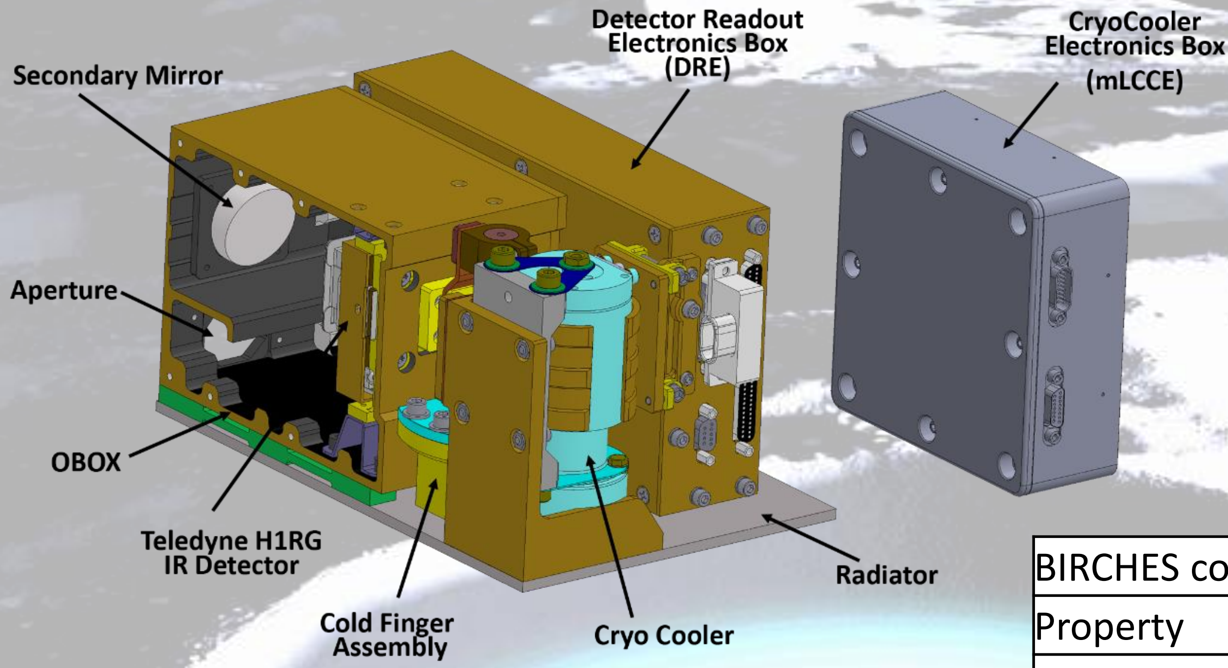
Species	µm	description
Water Form, Component		
water vapor	2.738	OH stretch
	2.663	OH stretch
liquid water	3.106	H-OH fundamental
	2.903	H-OH fundamental
	1.4	OH stretch overtone
	1.9	HOH bend overtone
	2.85	M3 Feature
	2.9	total H_2O
hydroxyl ion	2.7-2.8	OH stretch (mineral)
	2.81	OH (surface or structural)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



Ice Cube measurements will encompass the broad 3 um band to distinguish overlapping OH, water, and ice features. Will have near 10 nm resolution in this band

Yellow = water-related features in the 3 micron region

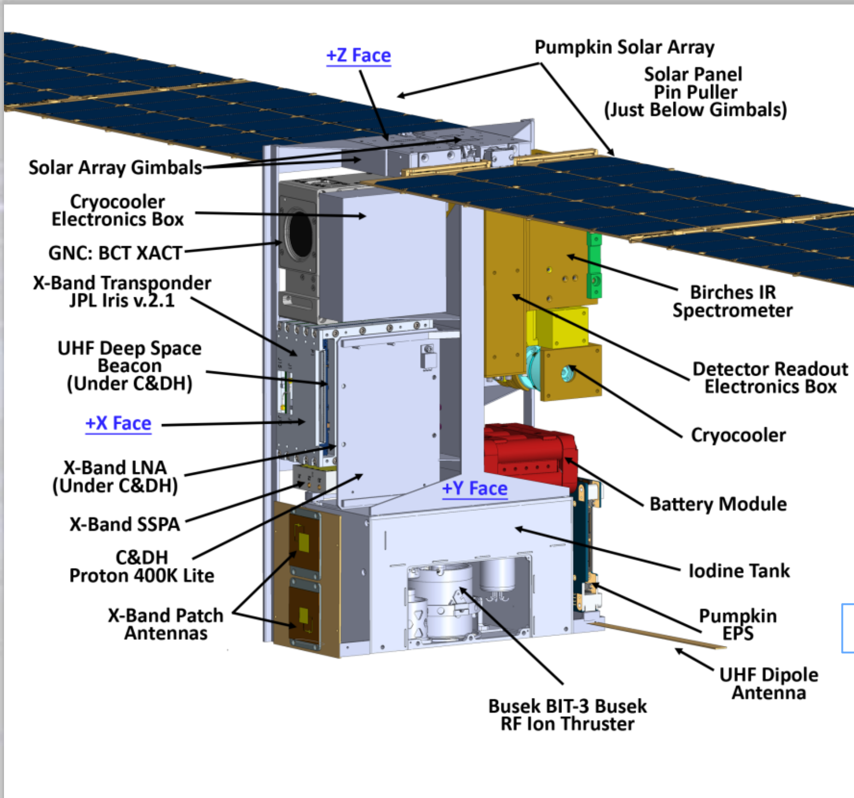
Subsystems Accomplishments - BIRCHES IR SPECTROMETER

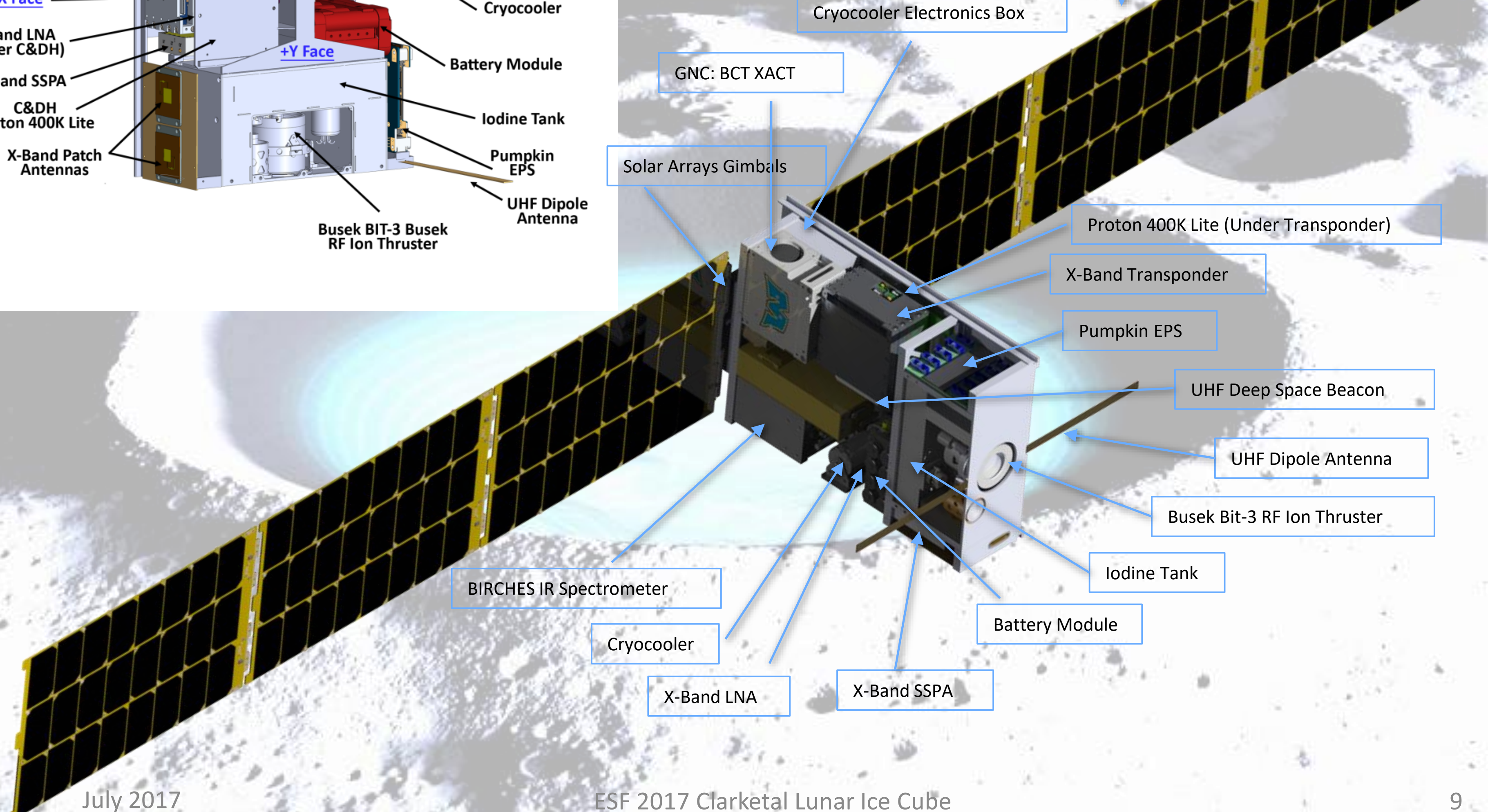


BIRCHES compactness		
Property	Ralph	BIRCHES
Mass kg	11	3
Power W	5	#10-20 W
Size cm	49 x 40 x 29	10 x 10 x 15
# includes 3 W detector electronics, 1.5 W AFS controller, 5-10 W cryocooler		

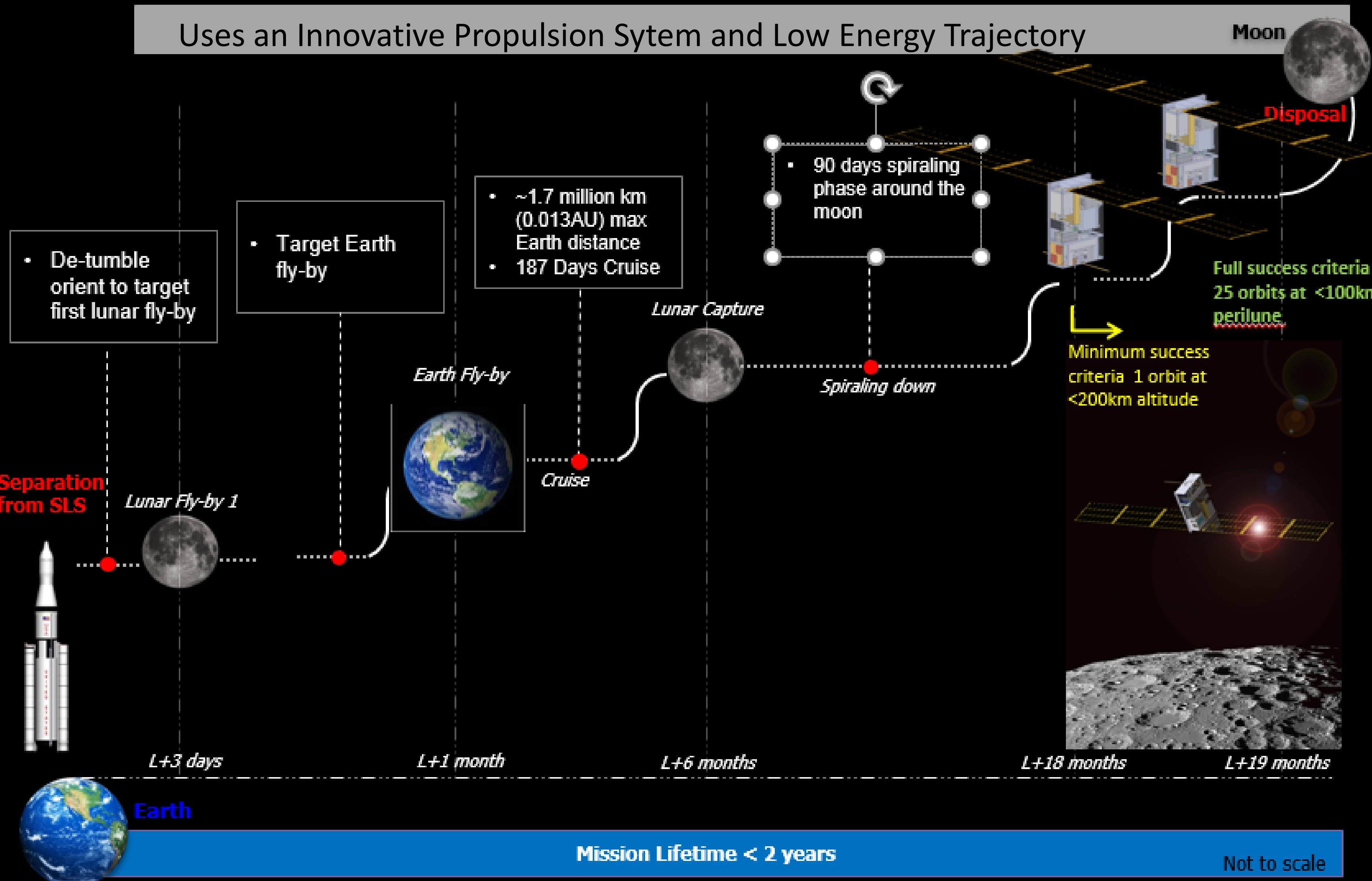
- Design Nearing Completion
  - ✓ Optics System Design Complete
  - ✓ Detector Electronics Complete
  - ✓ Cryogenics System Challenges Nearly Resolved
- Communication Interface Control Document Drafted
- Most flight parts have been ordered. Remaining flight components (Optical box (OBOX) chassis, Adjustable Field Stop (AFS) components, Mirrors, Cryo-cooler pump and cold finger assembly) to be ordered in April (May for the mirrors).
- ETU, Power Distribution Unit (PDU) , and Analog Processing Unit (APU) Cards Assembled

Lunar Ice Cube Bus





Lunar IceCube ConOps

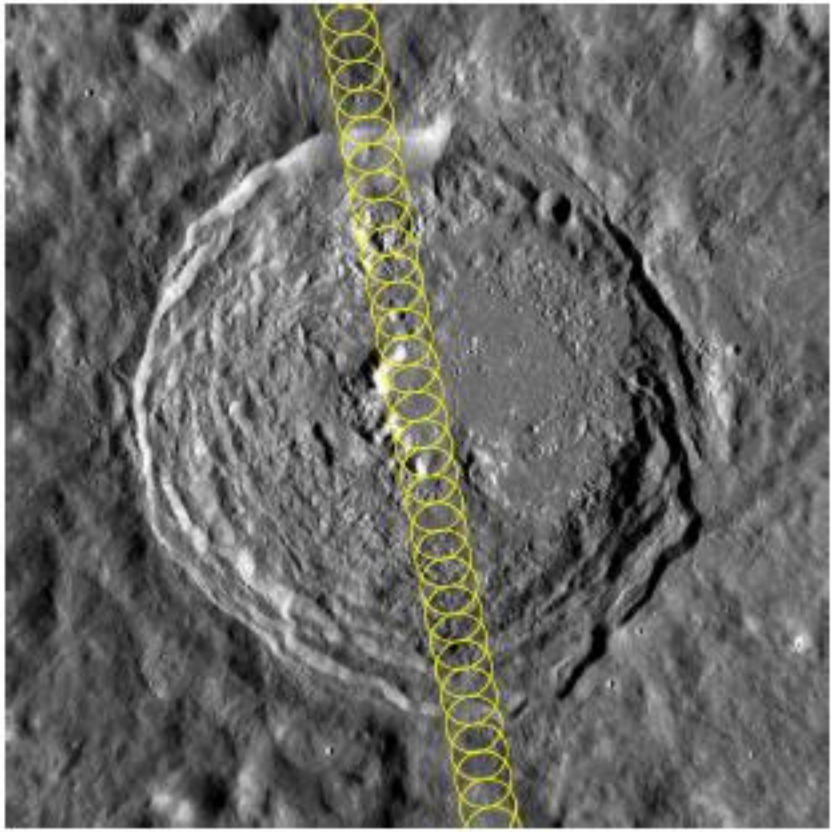


BIRCHES Observation Requirements

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

Current Challenges

Thermal: Progress: Nominally, can maintain BIRCHES and spacecraft components within required temperature ranges. Challenge: Stationkeeping is needed to maintain required lunar orbit. Ten hours will be needed after stationkeeping maneuver before instrument can operate within required temperature range, affecting two orbits of data-taking. Determining minimum frequency for stationkeeping. Mass expended to solve thermal problems (mostly) means we now have no margin.

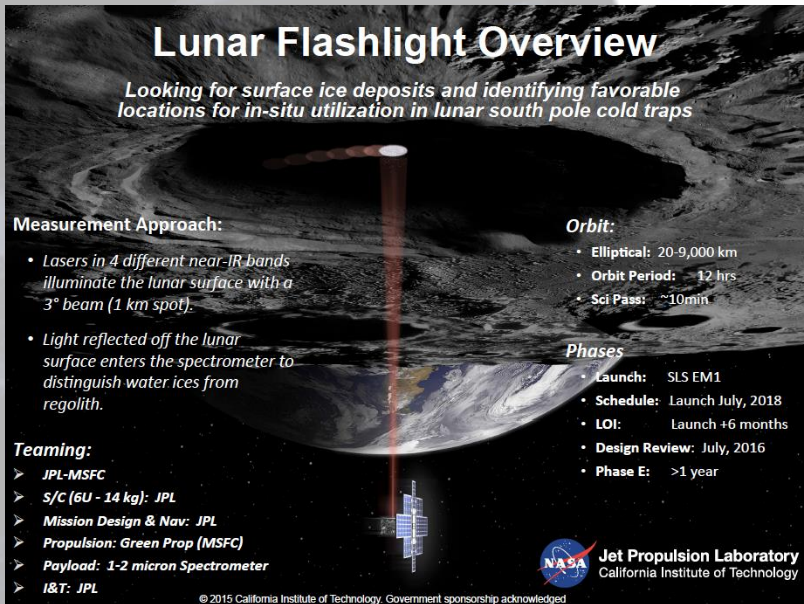
Optics: Progress: Now minimum resource cover solution to prevent sunlight from entering instrument. Adjustable Field Stop design now allows window spot size to be maintained over changes in altitude from 100 to 1000 km. Challenge: Impact of Delta T on all aluminum optics thought to be acceptable but needs to be determined.

Human-rated launch vehicle: Progress: Very high Vibration and Shock requirements mitigated by deployer design and original margins were very high. Challenge: Very large survival temperature range in requirements documents: could be partially mitigated by 'rolling' spacecraft once Orion deployed +1.5 hours) Solutions being negotiated.

COTS usage challenge: Some COTS subsystems reluctant to provide interface information required to mitigate potential severe risk. Example: pumpkin EPS impact on BIRCHES.

Data Management: PDS requirement at PDR presents major challenges and requires additional funding for Ground Data System, Science Data System, and NAIF/SPICE support. Progress: additional funds will be provided to produce EDRs and SPICE/NAIF kernels. Challenge: **We will need to leverage OTHER RESOURCES for data analysis.**

Other EM1 Mission Complimentarity



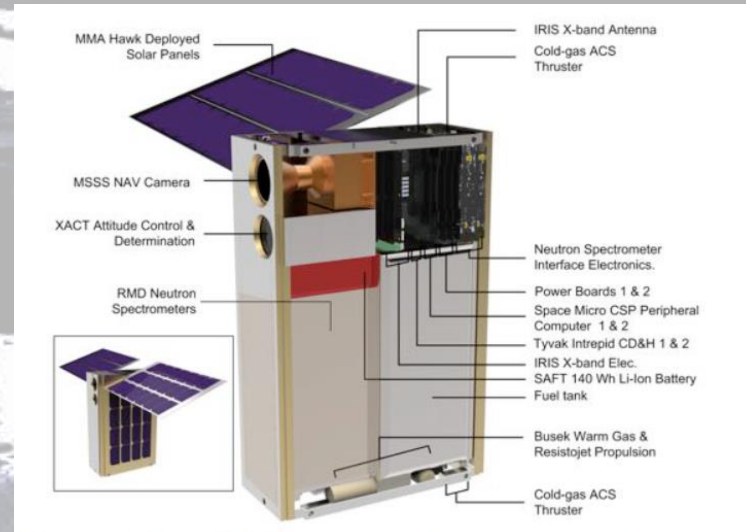


Figure 1: LunaH-Map cut-away showing spacecraft components and configuration. Inset image shows LunaH-Map deployed configuration.

Lunar Flashlight: Detect surface ice for PSRs polar region by measuring laser stimulated emission at several ice-associated lines.

LunaH Map: Detect ice in top layer (tens of centimeters) of regolith for PSRs polar region by measuring decrease in neutron flux (anti-correlated with protons) using neutron spectrometer.

Lunar IceCube: Determine water forms and components abundances as a function of time of day, latitude, and lunar regolith properties using broadband point spectrometer.

Conclusions

- BIRCHES measures variations in liquid water, ice, OH distribution across the lunar surface as function of time of day (temperature and illumination) as well as providing basis for constraints for existing global/local volatile production/interaction models
- Utilizes MSU cubesat bus with Busek propulsion and commercial subsystems modified for deep space, GSFC instrument and flight dynamics expertise with low energy manifolds to lunar capture, and JPL science PI and deep space communication expertise
- EM1 deployed Lunar Ice Cube lunar orbiter will deliver high priority measurements on lunar volatiles via a HEOMD NextSTEP mission selected to demonstrate technology for propulsion and compact volatile-detecting instrument capability
- Creating a tailored solution with a standard platform.

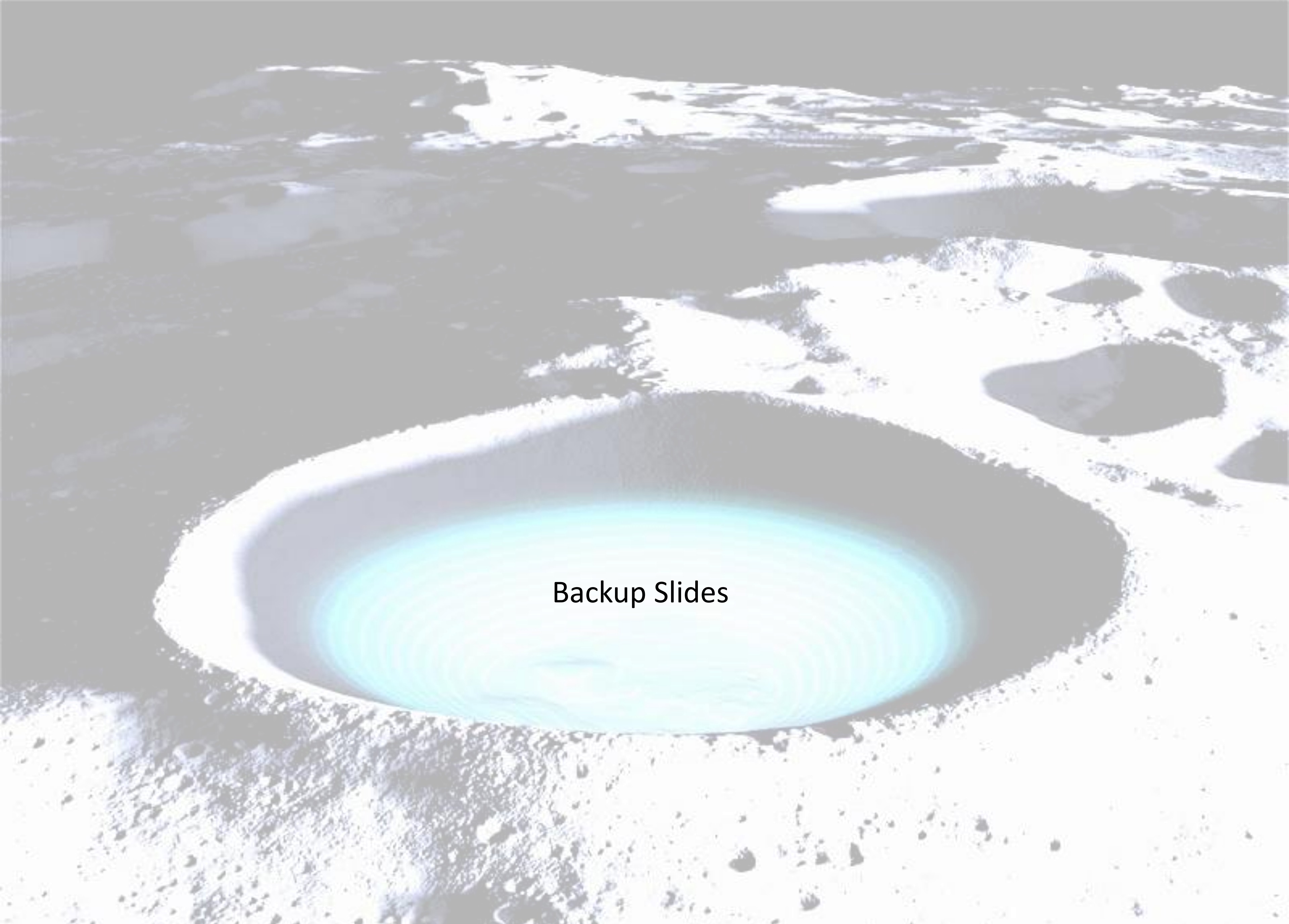
LunarCubes Are Back!!!!

CDW San Luis Obispo in April 2018

Your challenging science mission requirements needed

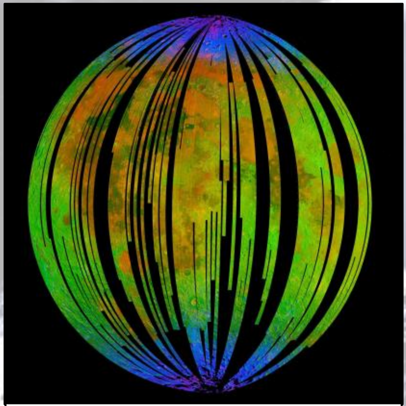
pamela.e.clark@jpl.nasa.gov

Backup Slides



Lunar IceCube versus Previous Missions

Mission	Finding	IceCube
Cassini VIMS, Deep Impact	surface water detection, absorption vs tiime of day implying variable hydration	water & other volatiles, fully characterize 3 μm region as function of several times of day for same swaths over range of latitudes w/ context of regolith mineralogy and maturity, radiation and particle exposure, for correlation w/ previous data
Chandrayaan M3	H2O and OH (<3 microns) veneer in mineralogical context nearside snapshot at one lunation	
LCROSS	ice, other volatile presence and profile from impact in polar crater (greater depth)	
LP, LRO, LEND LAMP DVNR LOLA LROC, LADEE	H+ in first meter (LP, LEND) & at surface (LAMP) inferred as ice (cold trap) abundance via correlation with temperature (DIVINER), PSR and PFS (LROC, LOLA), H exosphere (LADEE)	

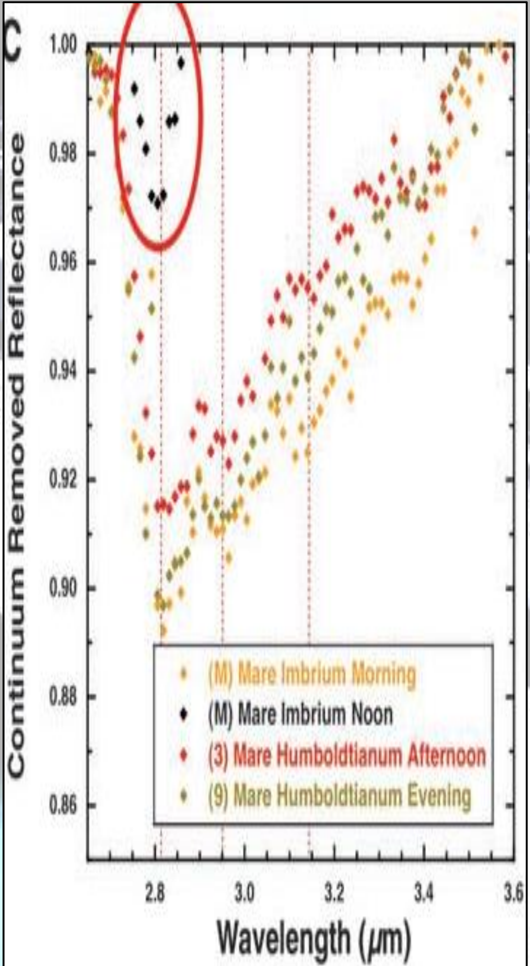


M3 'snapshot' lunar nearside indicating surface coating OH/H_2O (blue) near poles (Pieters et al, 2009)

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

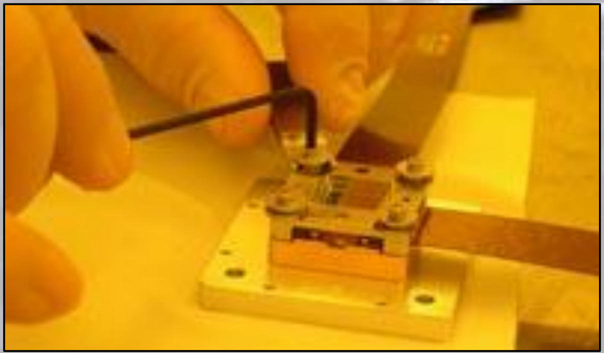
Compound	Molecules cm^{-2}	Relative to H_2O(g)*
H2O	5.1(1.4)E19	100%
H2S	8.5(0.9)E18	16.75%
NH3	3.1(1.5)E18	6.03%
SO2	1.6(0.4)E18	3.19%
C2H2	1.6(1.7)E18	3.12%
CO2	1.1(1.0)E18	2.17%
CH2OH	7.8(4.2)E17	1.55%
CH4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

*Abundance as described in text for fit in Fig 3C

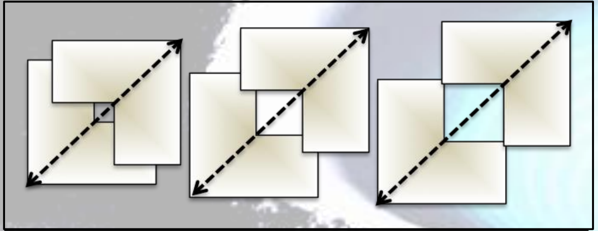


Early evidence for diurnal variation trend in OH absorption by Deep Impact (Sunshine et al. 2009) which will be geospatially linked by Lunar IceCube.

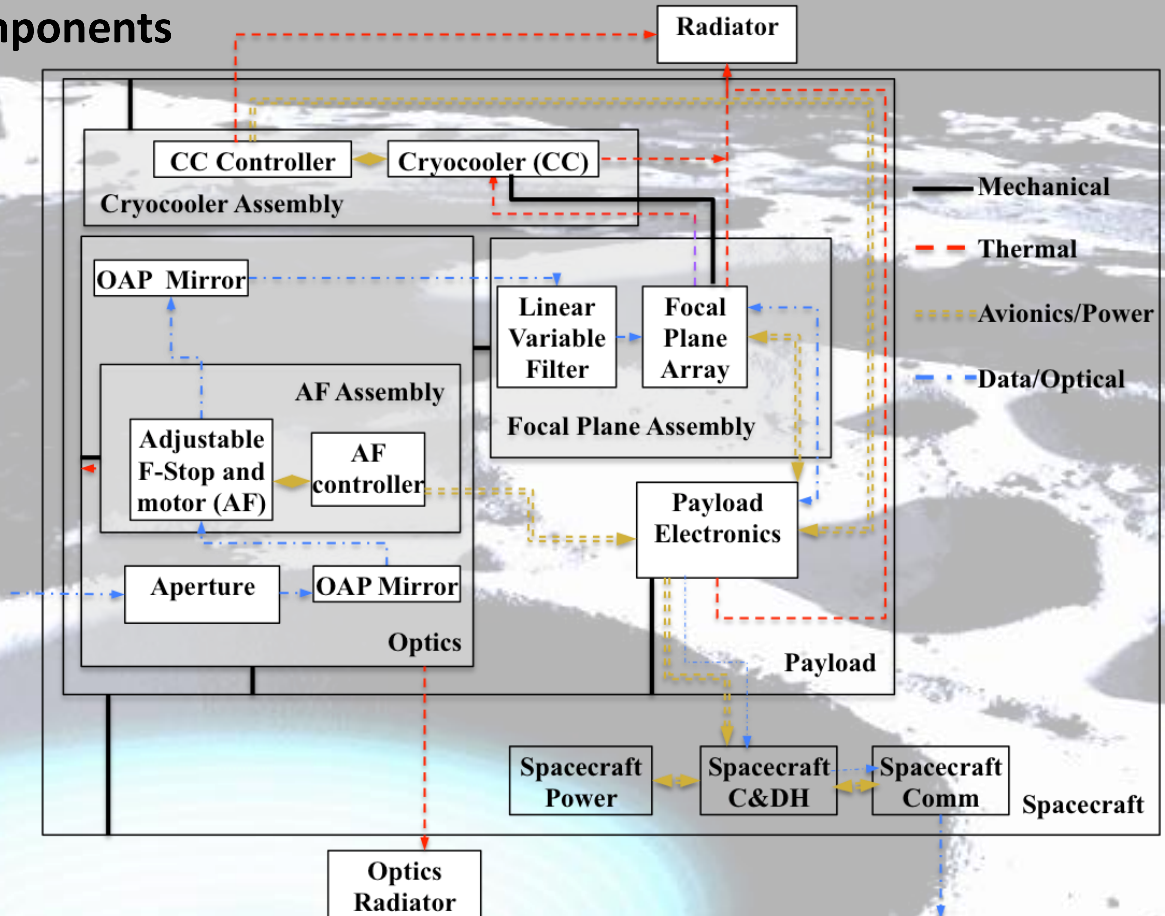
Spectrometer Schematic and Components



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

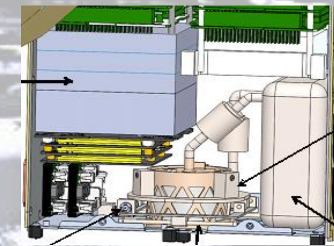


BIRCHES Analog Processing Unit (APU) (top)

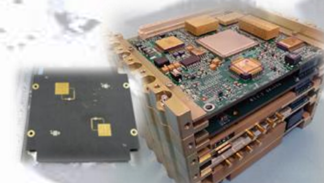
COTS AFRL developed AIM SX030 microcryocooler with cold finger to maintain detector at ≤115K and iris controller

Bus Components

Thermal Design: with minimal radiator for interior the small form factor for BIRCHES means that interior experiences temperatures well within 0 to 40oC. Optics box which has a separate radiator to keep it below 220K. Initial thermal modeling funded via GSFC IRAD work.

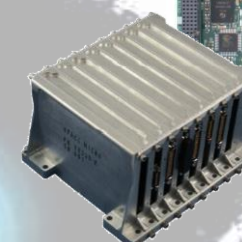


Propulsion: 2U Busek Gimbaled Iodine Ion Propulsion Drive (EP) with external e-source to offset charge build up. Models indicate no contamination problem.

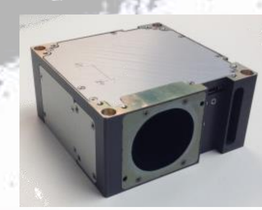


Communication, Tracking: X-band, JPL Iris Radio, dual X-band patch antennas. MSU has 21-m dish that is becoming part of the DSN. Anticipated data rate 128 kb/s

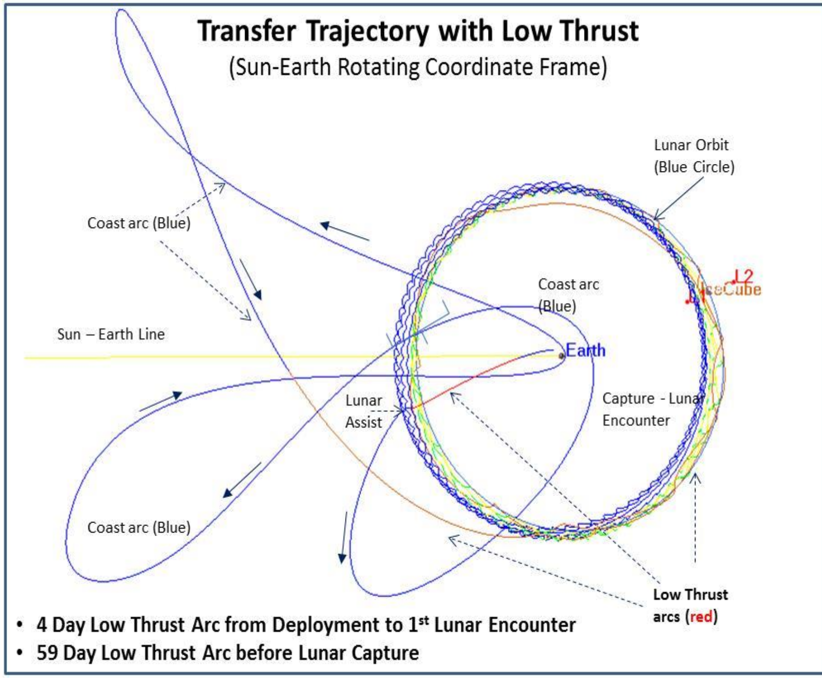
C&DH: Space Micro Proton 400K.

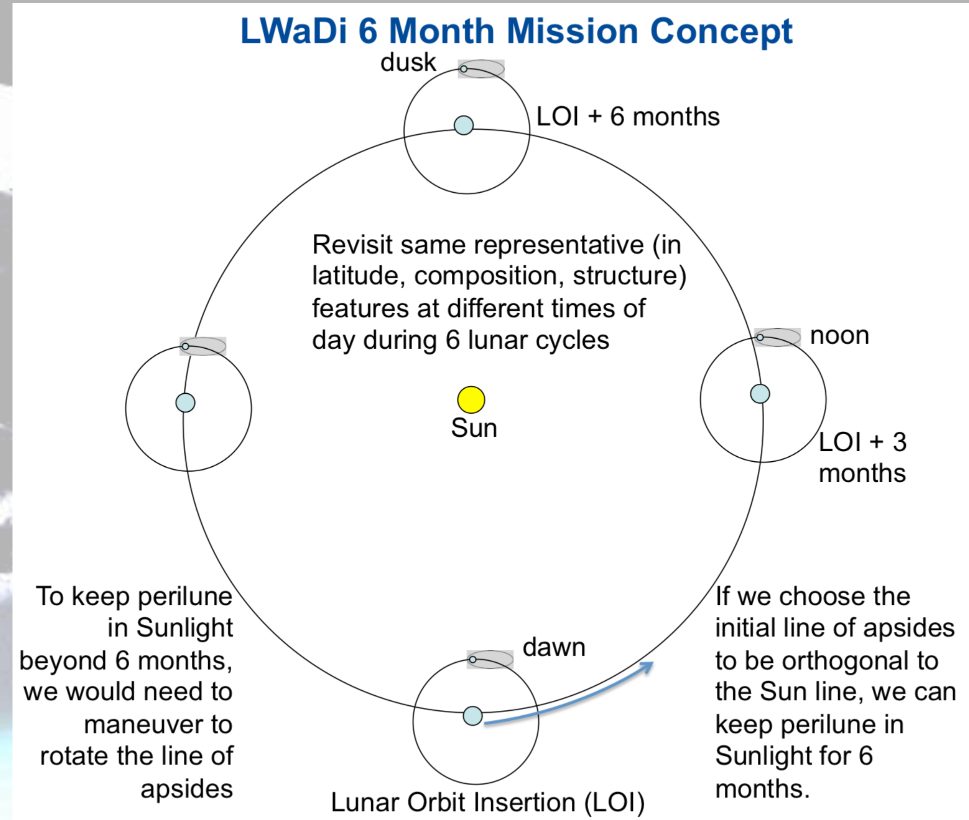


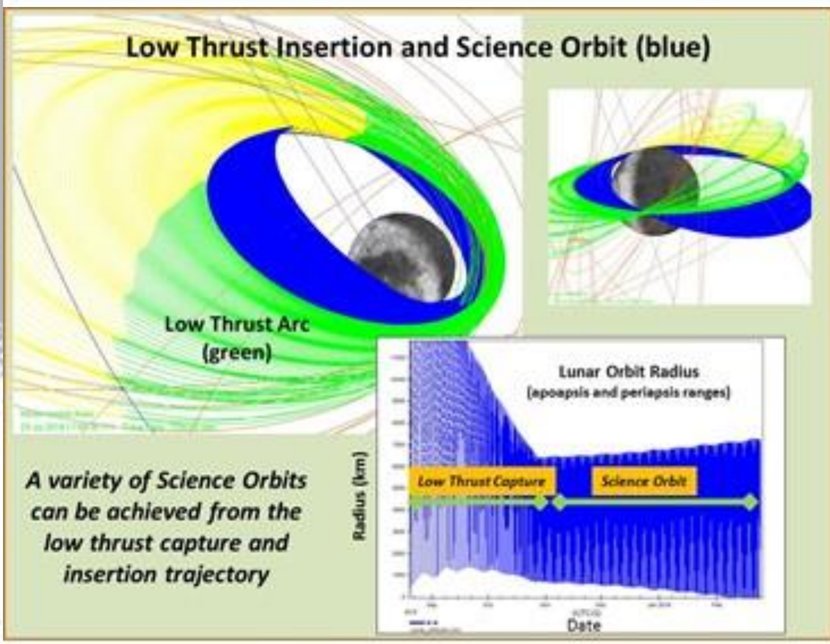
GNC/ACS: Modified Blue Canyon modified XACT. Multi-component (star trackers, IMU, RWA) packages. Stated Spacecraft pointing accuracy ±0.007 deg(1-sigma)

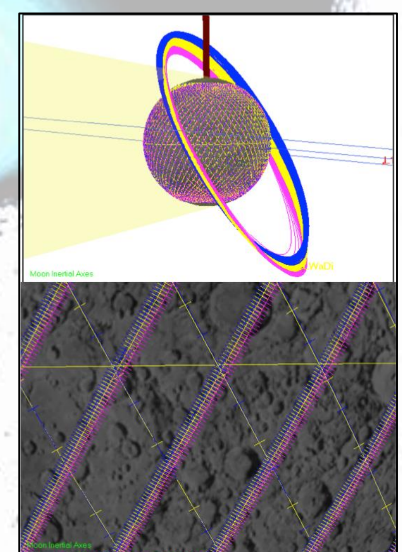


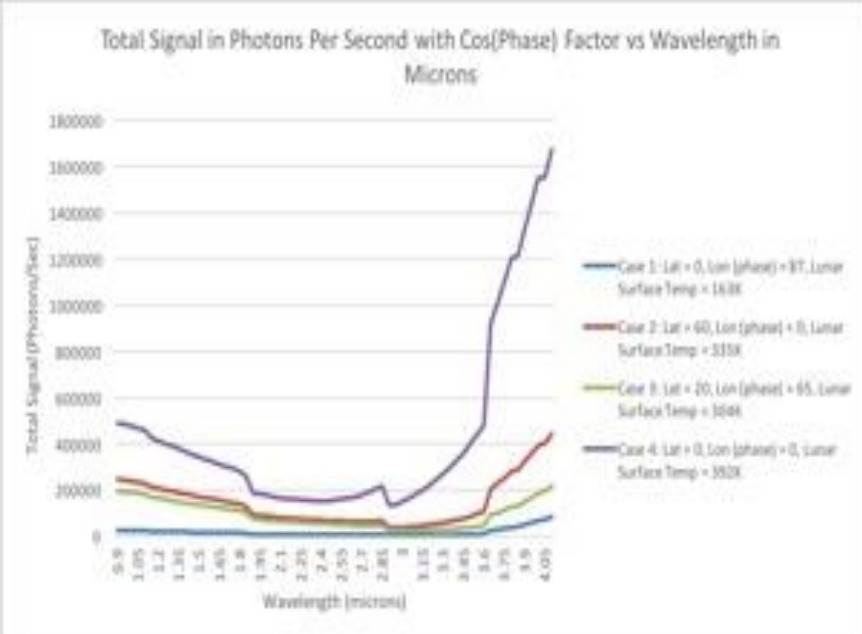
Power System: Pumpkin Custom Power System (Panels, Gimbals, EPS)

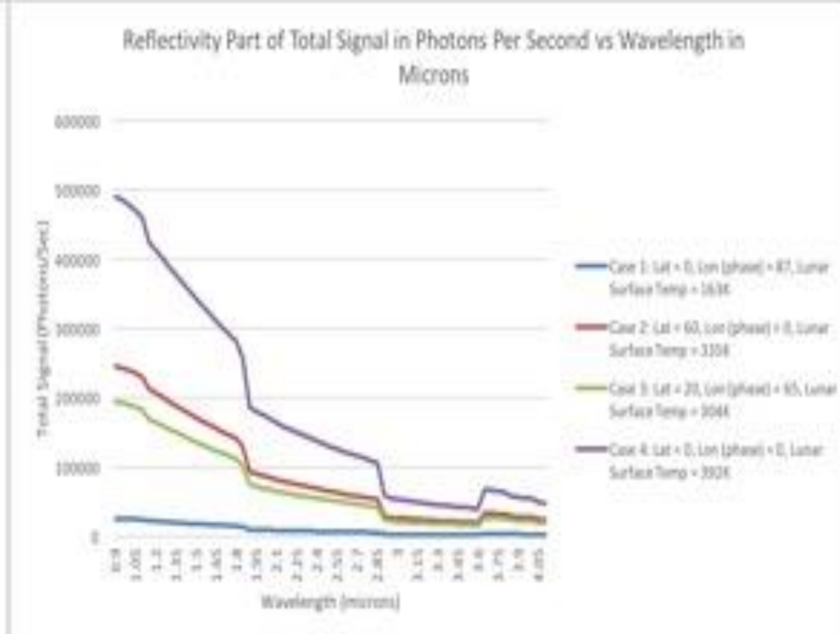

Transfer Trajectory with Low Thrust
(Sun-Earth Rotating Coordinate Frame)
Lunar Orbit (Blue Circle)
Coast arc (Blue)
Coast arc (Blue)
L2
IceCube
Sun – Earth Line
Earth
Lunar Assist
Capture - Lunar Encounter
Coast arc (Blue)
Low Thrust arcs (red)
• 4 Day Low Thrust Arc from Deployment to 1st Lunar Encounter
• 59 Day Low Thrust Arc before Lunar Capture


LWaDi 6 Month Mission Concept
dusk
LOI + 6 months
Revisit same representative (in latitude, composition, structure) features at different times of day during 6 lunar cycles
noon
Sun
LOI + 3 months
To keep perilune in Sunlight beyond 6 months, we would need to maneuver to rotate the line of apsides
dawn
If we choose the initial line of apsides to be orthogonal to the Sun line, we can keep perilune in Sunlight for 6 months.
Lunar Orbit Insertion (LOI)


Low Thrust Insertion and Science Orbit (blue)
Low Thrust Arc (green)
A variety of Science Orbits can be achieved from the low thrust capture and insertion trajectory
Lunar Orbit Radius (apoapsis and periapsis ranges)
Radius (km)
Low Thrust Capture
Science Orbit
Date







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