CubeSats and Science Requirements Driven Deep Space Missions: A Marriage made in Heaven?

Example: IceCube Lunar Orbiter with BIRCHES (Broadband InfraRed Compact High-Resolution Exploration Spectrometer) NASA NextSTEP (Next Space Technologies for Exploration Partnerships) LunarCubes Mission and Instrument Concept

P.E. Clark, IACS/CUA/NASA GSFC and Flexure Engineering, Science PI

B. Malphrus, Morehead State University, PI

Morehead State University: B. Twiggs, Jeff Kruth, Kevin Brown, R. McNeill, B. Kroll
NASA/GSFC: A. Mandell, R. MacDowall, C. Brambora, D. Patel, S. Banks, D. Folta, P. Calhoun, P. Coulter
Busek: K. Hohman, V. Hruby

Next Step Selectee Announced March 30, 2015!

Why Lunarcubes?

Using the Cubesat paradigm to build user requirements driven ‘pathfinders’ for low-cost multi-platform mission concepts that will ultimately provide next generation exploration through the use of temporal and spatially distributed measurements.

Providing access to deep space via the Moon as nearby analogue, technology testbed, and gateway to the solar system.

Providing a low-cost alternative for high science yield missions at a time of declining funding and increasing costs for conventional missions.

Taking advantage of the decade long evolution of the cubesat model from standardized kits to science-driven, multi-institutional, multi-platform collaborations for LEO applications.

Examining the use of cubesat hardware/software for missions that are a representative cross-section of lunar, Mars, and other applications at varying degrees of difficulty (flyby, probe, orbiter, lander).

identifying modifications and new technology needed to support a science-driven deep space mode.

Looking for NASA to expand the CubeSat Launch Initiative which provides launch opportunities for cubesats to LEO as secondaries at no cost, to GEO and beyond.

designing a deep space prototype bus, and prototype for a lunar orbiter missions.

Building on the exploding interest in cubesat as seen in growing popularity of our LunarCubes Workshops over the last 3 years.

Deep Space CubeSats And Challenges

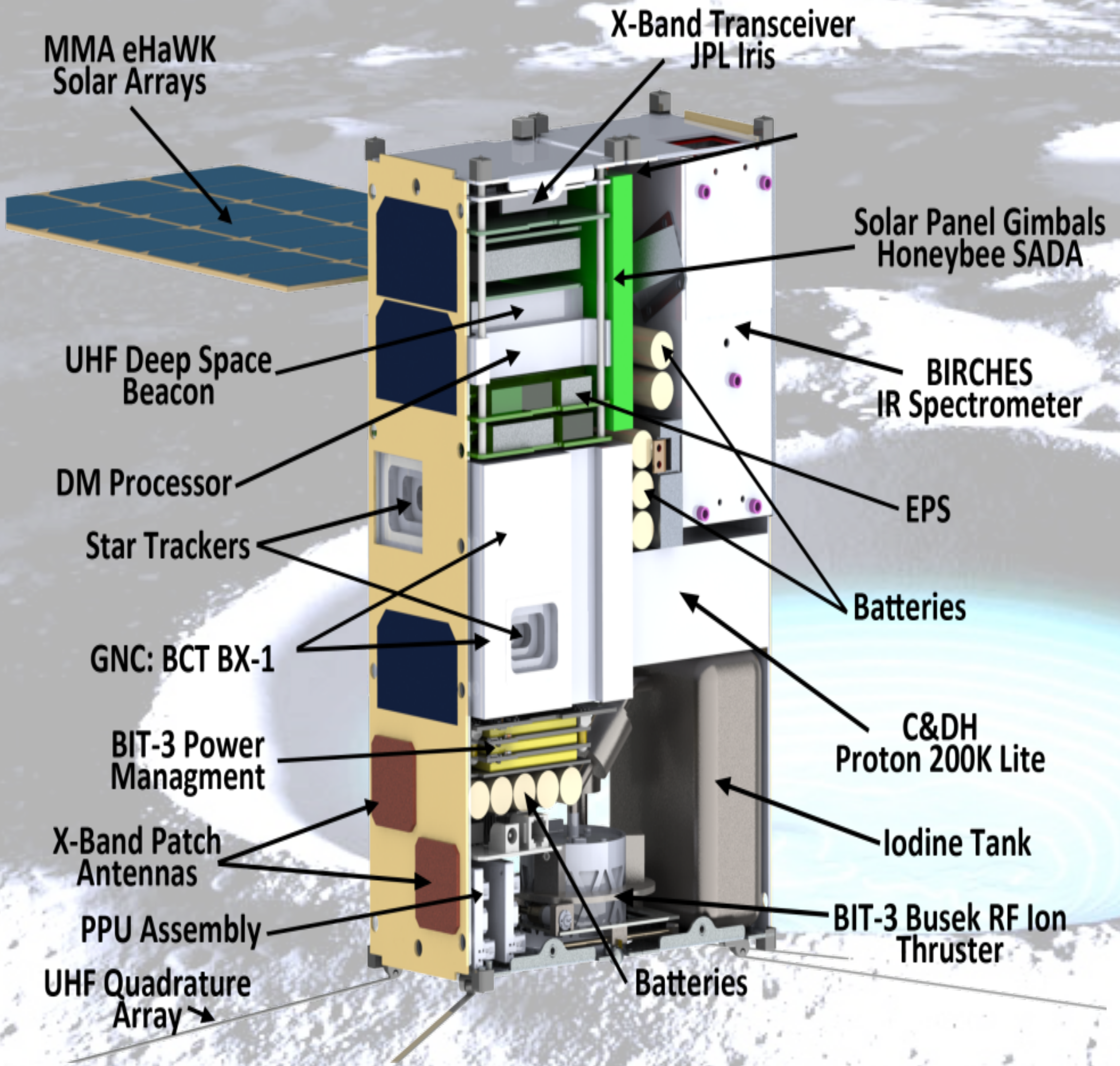
Deep Space CubeSats to date:

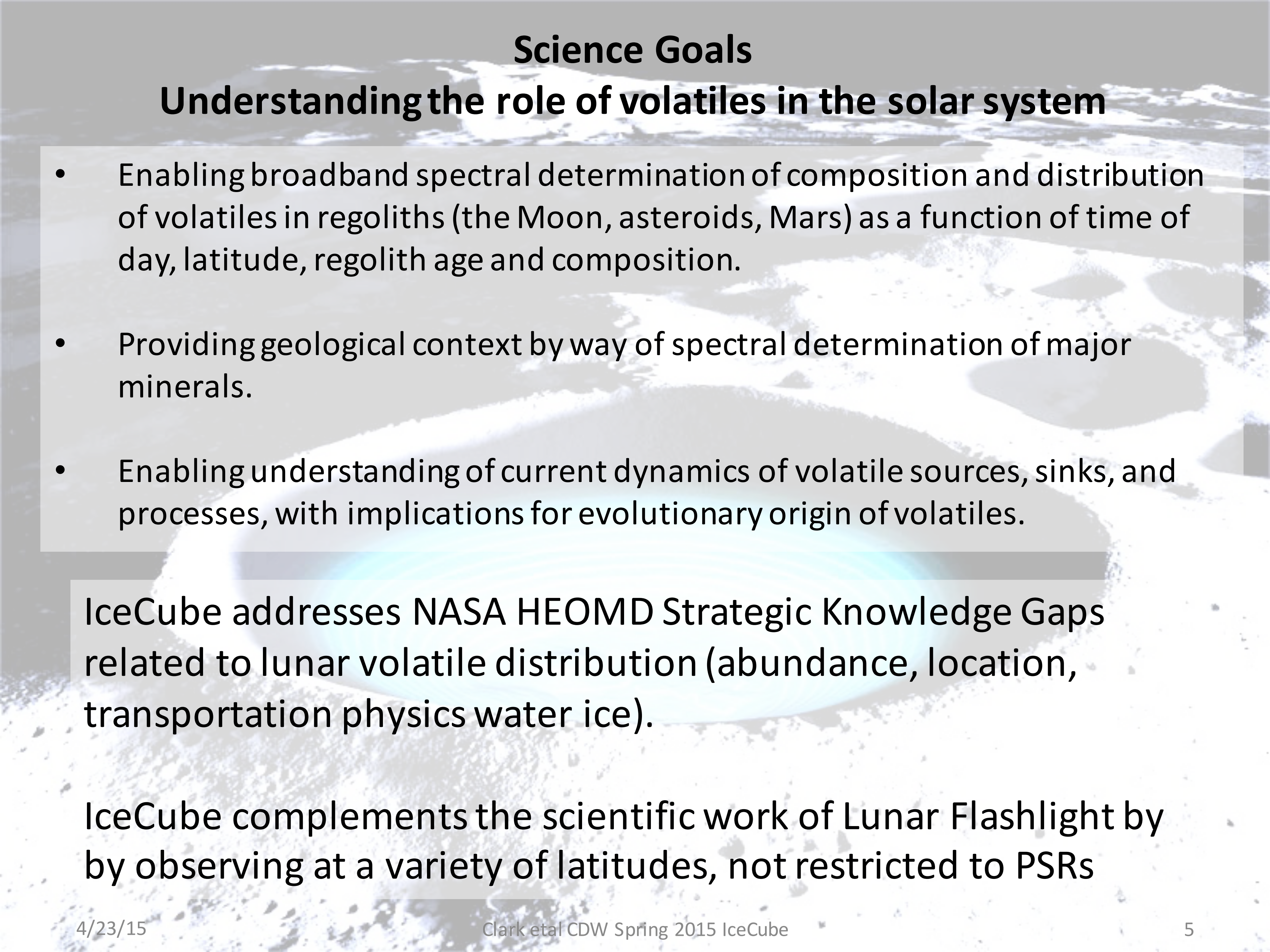
Announced: INSPIRE (2 3U); 11 EM1 releases (6U) including 3 HEOMD AES selected (Lunar Flashlight, NEA Scout, BioSentinel) plus 8 others TBS (SMD PDS SIMPLEx (1), SMD Heliophysics HTIDS (1), HEOMD NextStep (1), OCT Centennial Challenges (several)); Europa mission secondaries
Likely: Surviving GLXP/Catalyst lander deck, leg, or orbit secondaries; Mars mission secondaries; Deep Space Scouts from 100 EM1 proposals pent-up demand

As in NASA's first decade, all 'prototypes' of these 'shoeboxes' must, to get beyond LEO (launch, orbit, orbital formation flying), demonstrate the following:

Operate in Deep Space Radiation Environment
Operate in Extreme Target Thermal Environment (particularly the Moon)
Manage Deep Space Communication
Manage Deep space Navigation and Tracking
Perform Deep Space Maneuvers, Orbital Insertion and Orbit Maintenance
Manage a variety of onboard propulsion systems: (solar sail, ion drive, microcathode, electrospray)
Manage onboard active attitude control systems
Perform Onboard Processing
Find Capable yet Compact, Low-Cost, Low-power Payloads
Harness CubeSat (Class D) development model

Morehead CubeSat Bus





Science Goals
Understanding the role of volatiles in the solar system

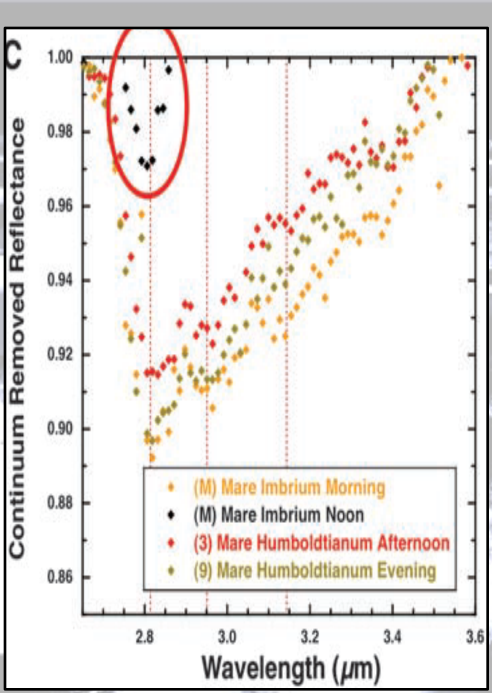
- Enabling broadband spectral determination of composition and distribution of volatiles in regoliths (the Moon, asteroids, Mars) as a function of time of day, latitude, regolith age and composition.

- Providing geological context by way of spectral determination of major minerals.

- Enabling understanding of current dynamics of volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles.

IceCube addresses NASA HEOMD Strategic Knowledge Gaps related to lunar volatile distribution (abundance, location, transportation physics water ice).

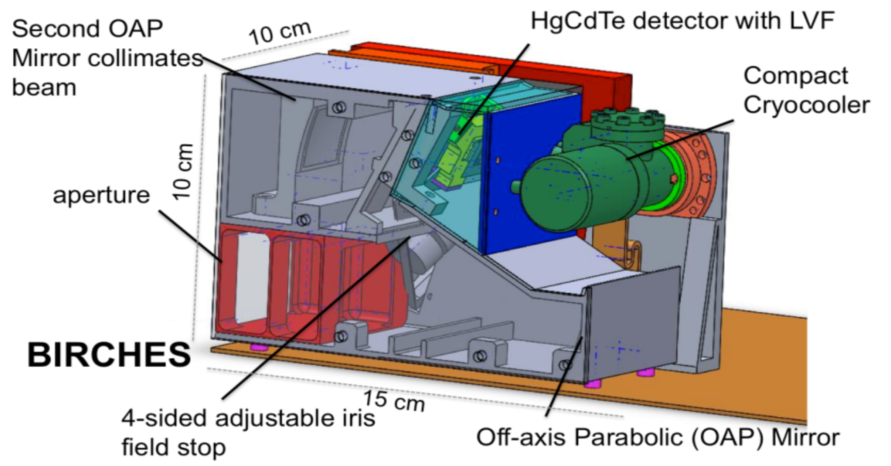
IceCube complements the scientific work of Lunar Flashlight by by observing at a variety of latitudes, not restricted to PSRs



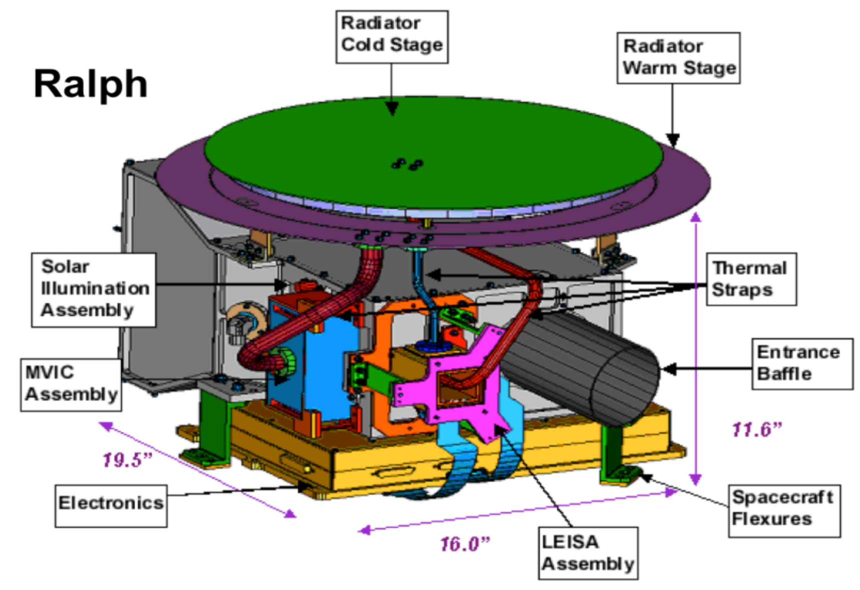
IceCube versus Previous Missions

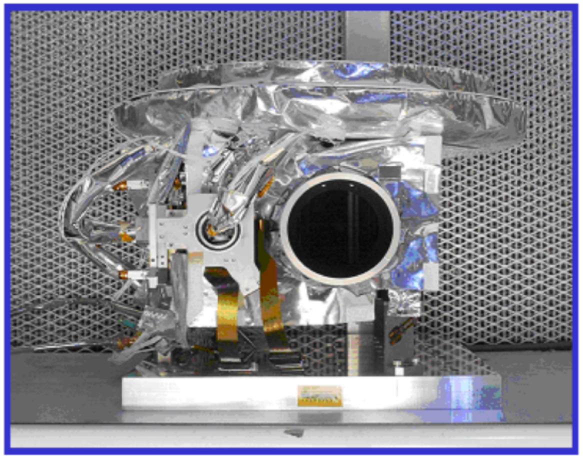
Mission	Finding	IceCube
Cassini VIMS, Deep Impact	surface water detection, variable hydration	water & other volatiles, fully characterize 3 μm region as function of several times of day for same swaths over range of latitudes w/ context of regolith mineralogy and maturity, radiation and particle exposure,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

- Broadband IR spectrometer with HgCdTe and compact line separation (LVF)
- Compact microcrycooler to ≤ 120K to provide long wavelength coverage
- compact optics box designed to remain below 220K
- OSIRIS Rex OVIRS heritage design

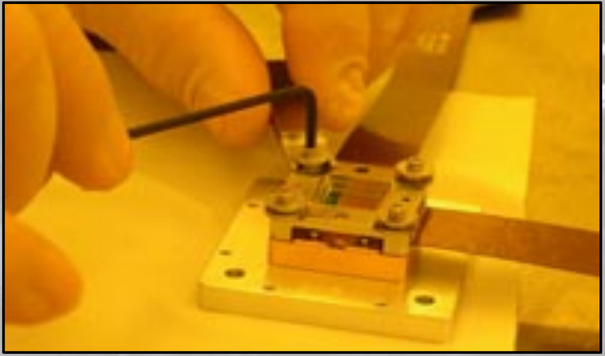


Property	Ralph	BIRCHES
Mass kg	11	2
Power W	5	<5#
Size cm	49x40x29*	10x10x15
*19.5x16.0x11.6 inches equivalent		
#includes 3W cryocooler		

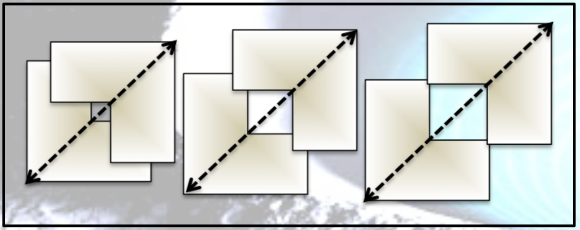




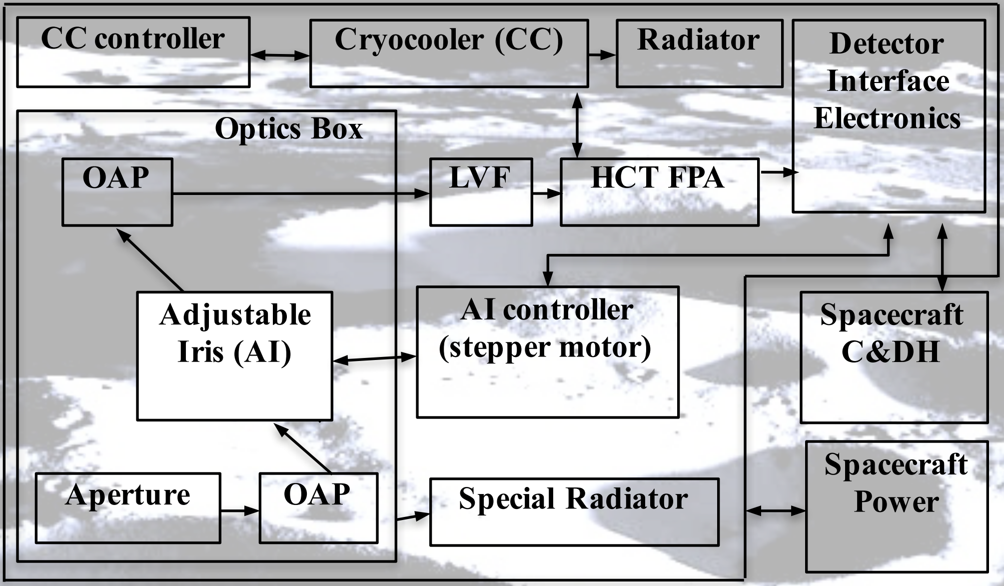
Spectrometer Components



BIRCHES utilizes a compact Teledyne H1RG HgCdTe FPA and JDSU linear variable filter detector assembly leveraging OSIRIS REx OVIRS.



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



CC controller

Cryocooler (CC)

Radiator

Detector Interface Electronics

Optics Box

OAP

LVF

HCT FPA

Adjustable Iris (AI)

AI controller (stepper motor)

Spacecraft C&DH

Aperture

OAP

Special Radiator

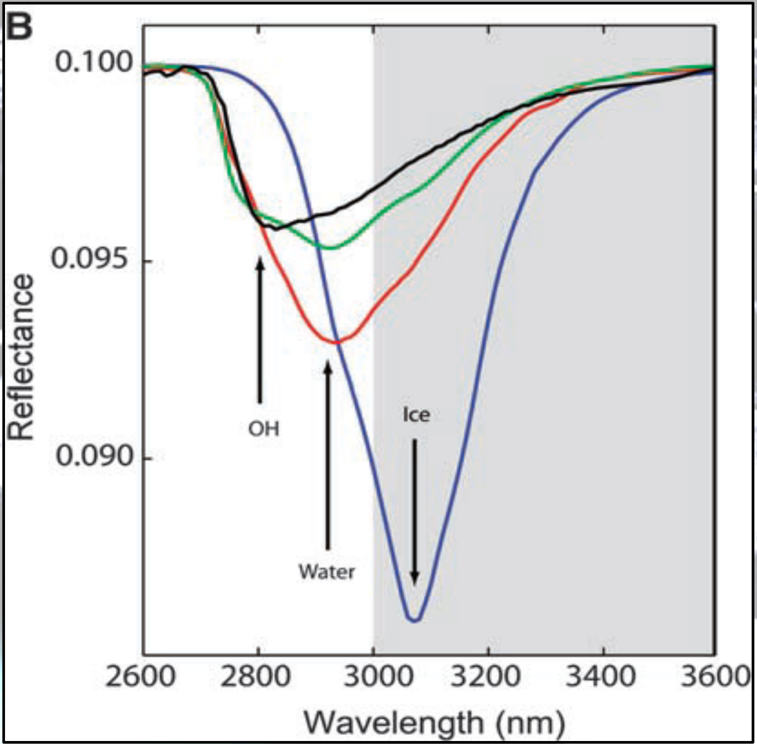
Spacecraft Power

BIRCHES block diagram illustrates simplicity and flexibility of design.

Off the shelf tactical cryocooler with cold finger to maintain detector at ≤140K

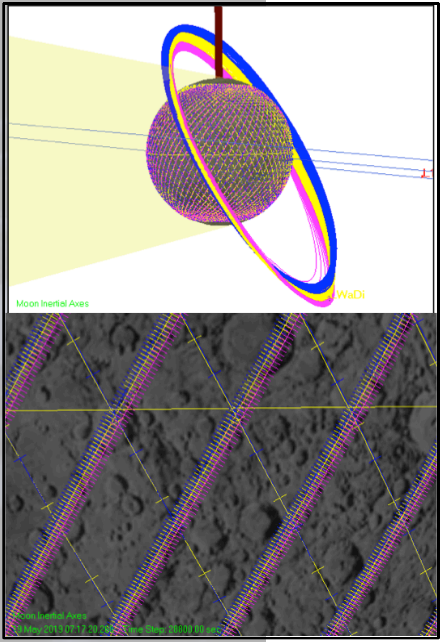
Table C.1 Water-, Volatile-, and Mineral-Related Bands

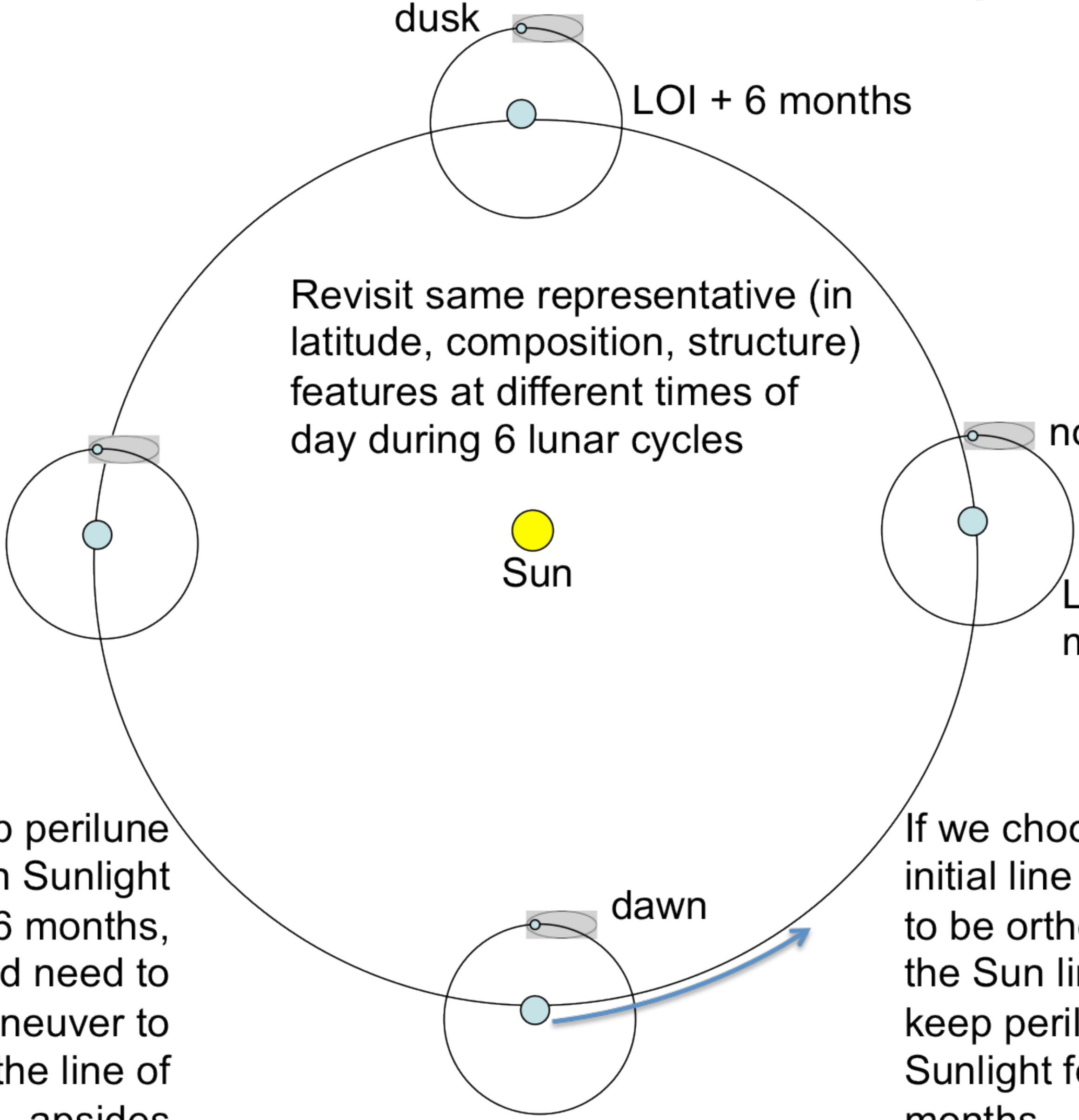
Species	**µm**	**description**
Water Form, Component		
water vapor	2.738	OH stretch
	2.663	OH stretch
liquid water	3.106	H-OH fundamental
	2.903	H-OH fundamental
	1.4	OH stretch overtone
	1.9	HOH bend overtone
	2.85	M3 Feature
	2.9	total H2O
hydroxyl ion	2.7-2.8	OH stretch (mineral)
	2.81	OH (surface 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 would be structural<bound<adsorbed<ice		



Ice Cube measurements will not cut off (Pieters et al. 2009) but encompass the broad 3 um band to distinguish overlapping OH, water, and ice features.

LWaDi 6 Month Mission Concept

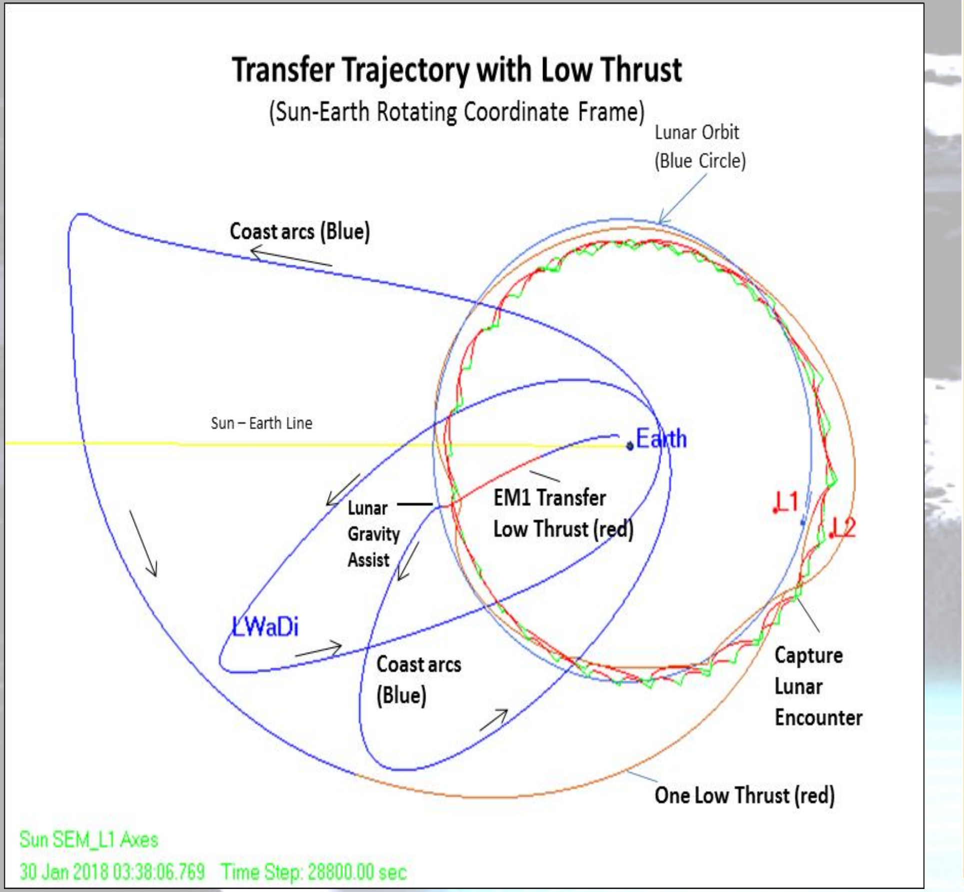




Revisit same representative (in latitude, composition, structure) features at different times of day during 6 lunar cycles

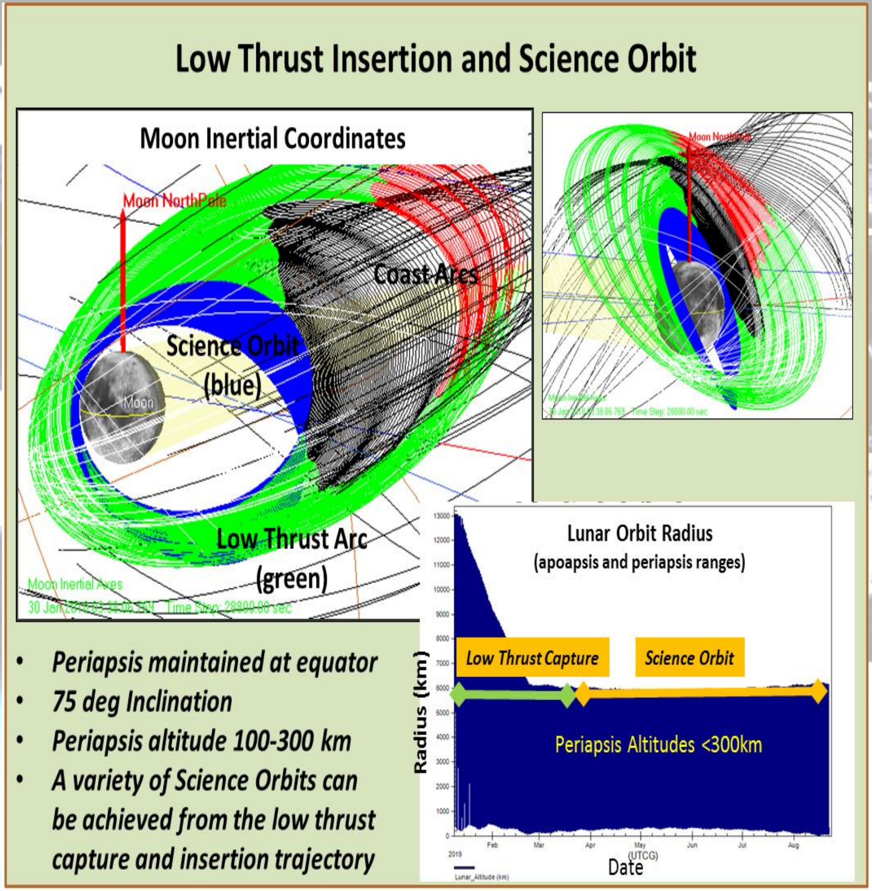
To keep perilune in Sunlight beyond 6 months, we would need to maneuver to rotate the line of apsides

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



Transfer Trajectory with Low Thrust

(Sun-Earth Rotating Coordinate Frame)



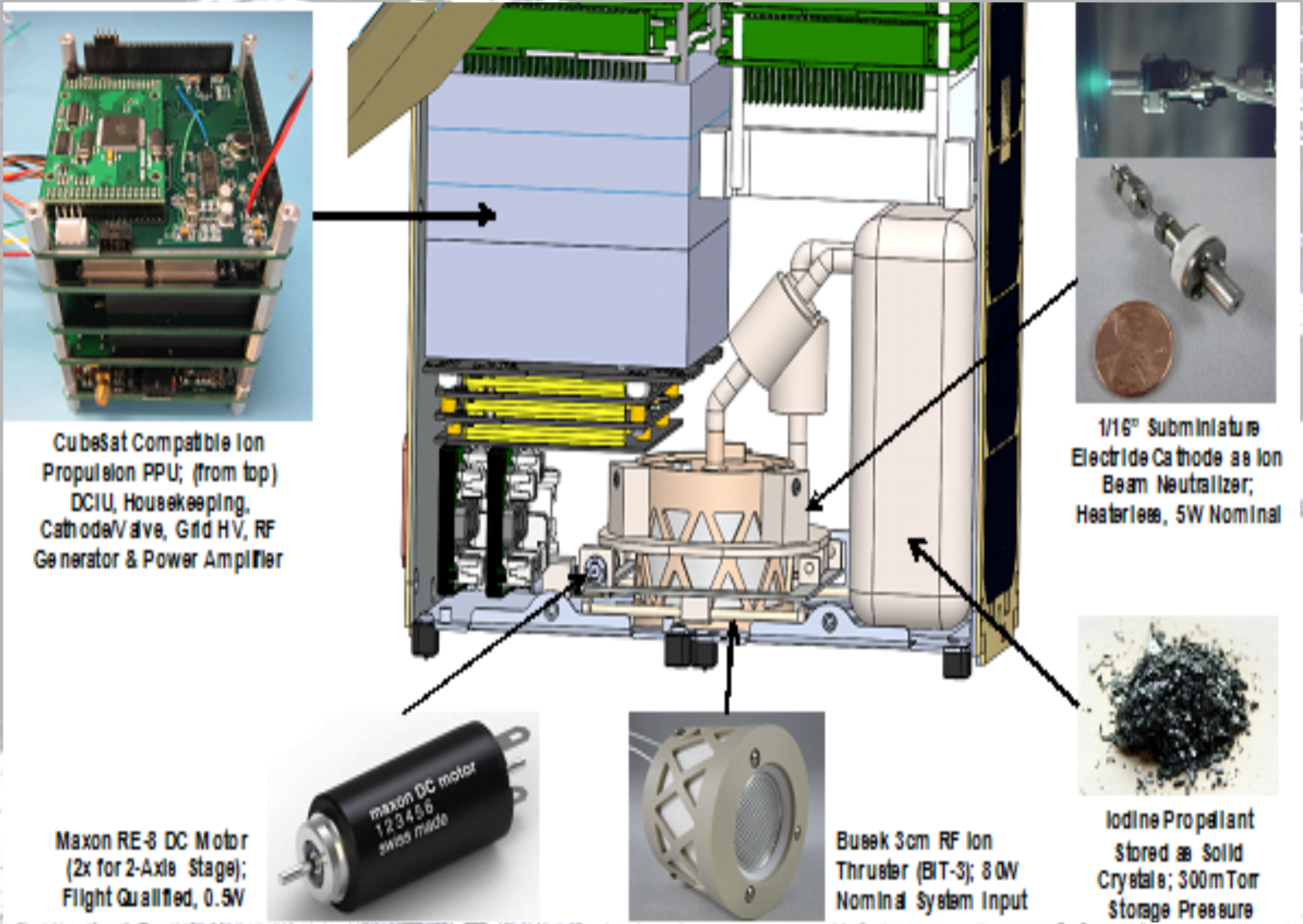
Low Thrust Insertion and Science Orbit

- *Periapsis maintained at equator*
- *75 deg Inclination*
- *Periapsis altitude 100-300 km*
- *A variety of Science Orbits can be achieved from the low thrust capture and insertion trajectory*

IceCube utilizes a minimal DV transfer trajectory harnessing expertise of GSFC flight dynamics.

IceCube lunar capture and science orbit designed by experienced GSFC flight dynamics team.

Busek Iodine ion propulsion system



CubeSat Compatible Ion Propulsion PPU; (from top) DCIU, Housekeeping, Cathode/Valve, Grid HV, RF Generator & Power Amplifier

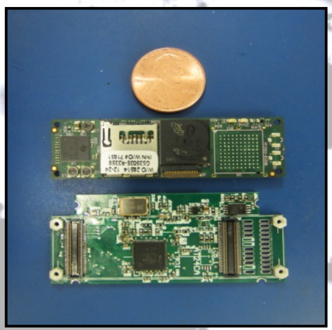
1/16" Subminiature Electride Cathode as Ion Beam Neutralizer; Heaterless, 5W Nominal

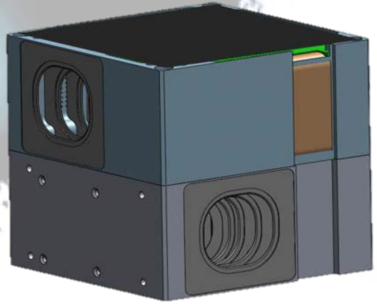
Maxon RE-8 DC Motor (2x for 2-Axis Stage); Flight Qualified, 0.5W

Busek 3cm RF Ion Thruster (BIT-3); 80W Nominal System Input

Iodine Propellant Stored as Solid Crystals; 300mTorr Storage Pressure

Bus Components





Thermal Design: with minimal radiator for interior the small form factor meant that interior experienced temperatures well within 0 to 40 degrees centrigrade, except for optics box which has a separate radiator.

Communication, Tracking: X-band, JPL Iris Radio, dual X-band patch antennas, X-band dish (trade availability, cost, dB, and DSN compatibility, live with the fact this hasn't flown in deep space)

C&DH: very compact and capable Honeywell DM microprocessor, at least one backup C&DH computer (trade volume, complexity, cubesat heritage, live with the fact this hasn't flown in deep space)

GNC/ACS: multi-component (star trackers, IMU, RWA) packages with heritage available, including BCT XB1, which can interface with thrusters (trade cost, volume, cubesat heritage, live with the fact this hasn't flown in deep space)

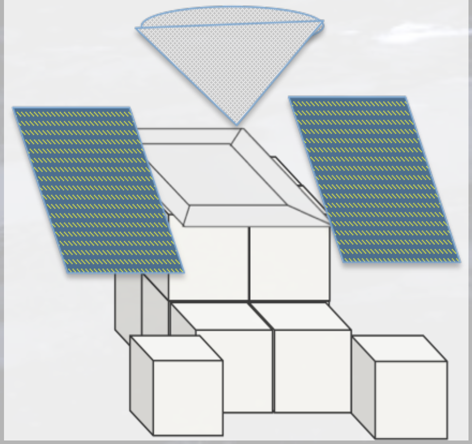
Table 4: Lunar IceCube Subsystems

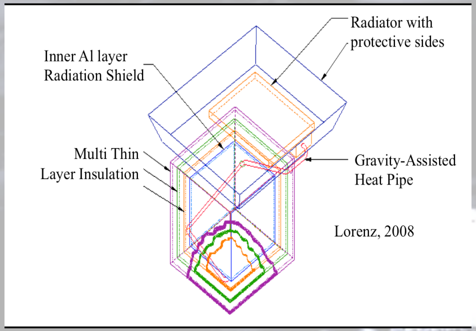
System	Mass	Volume (in Us)	Power Use	Rad Tolerance	Dollars*	Source
Structures, Thermal Management	1.2 kg	6U Exterior & Rings	N/A	N/A	69K	MSU
C&DH: Proton 200K Lite/ Custom Daughter BCT XB1 for ACS Control	0.36 kg	0.75 U	5 W	>100 krad	240K	Space Micro BCT XB1 MSU
Harnesses, cables, coatings, elastomerics	0.5 kg	Conformal w/in structure	N/A	N/A	12K	MSU
Power (Solar panels & Gimbals MMA HaWK 72 W Array	0.340kg x 2 Deployed 0.190kg x 2 Fixed (Side)	Deployable panels intrude 10 mm into structure (each)	N/A	TBD	185K	MSU + MMA
Solar Panel Drive Articulators HoneyBee SADA	0.40 kg x 2	10 x 10 x 0.65 cm (Each) (0.25U)	5 W	10 krad	Included Above	Honeybee Robotics-MMA
EPS + Batteries MSU + TBD	2.4 kg	0.5 U	Quiescent Draw = 10 mW	> 10 krad	36K	MSU
Propulsion: Busek BIT-3cm RF Ion Iodine	2.5 kg	2U	60W	TBD	1,000K	Busek
ACS/GNC: BCT XB1	2.1 kg	0.75 U	6.3W Cont.	TBD	250K	BCT XB1
Comms: JPL Iris	0.5 kg	0.5U + Antennas	12.8 W-Transponder 6.4 W- Receive	50 krad	500 K	JPL IRIS
IR Spectrometer	0.62 kg	1.5 U	<5 W	TBD	In budget	GSFC
Payload Processor: DM	0.350 kg	10 x 10 x 4 cm (0.25U)	2 W per processor continuous	Multiple processors (8) & middleware	68K	MSU/Honey well

EM1 Selectees to Date

Program	**Target, Description**	**Payload**	**Lead**
HEOMD NEXT STEP	Moon, orbiter, Ice Cube	broadband IR cryocooled.	Morehead State U/NASA GSFC/Busek
HEOMD AES	Lunar Flashlight orbiter. (Surface ices in permanently shadowed 'cold traps')	NIR instrument.	JPL
HEOMD AES	Near Earth Asteroid Scout	Imager to characterize asteroid dynamics and surface	JPL
HEOMD AES	BioSentinel	Radiation Exposure Induced Genetic Damage Experiment	NASA/Ames
HEOMD NEXT STEP	??	???	Lockheed Martin
SMD SIMPLEx			
STMD Centennial Challenges			

CLASS Cubesat Lunar Application Surface Station Concept (12U) (Assuming no RTGs)





Lorenz, 2008

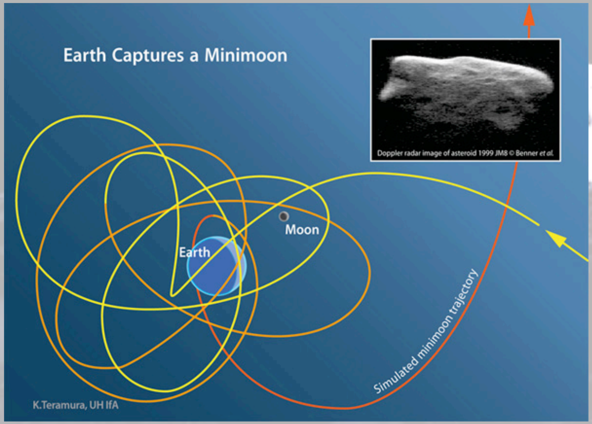
Reduction in mass and power for LEMS as new concepts developed

Design Regime	Conventional Electronics	MilSpec Cold Electronics	New Thermal Design	Compact 12U concept
Operational Limit C	-10	-40	-40	-40
Survival Limit C	-20	-50	-50	-50
Battery Mass kg	240	120	30	5 (3U)
Remaining Mass kg	260	260	70	12
Total Mass kg	500	380	100	15
Power W peak/minimum	50	30	65/10	10/2
Night Duty Cycle	None	None	10%	>10%

Payload Concept: Based on preliminary work, with state of the art thermal design, a 5 U payload of compact instruments, such as a small particle analyzer, electrical field instrument, and UV spectrometer, could be supported in a 12 U package with cubesat bus and deployables for power generation and communication (4 U), and 3 U for battery volume. With alternative power storage systems under development, a larger payload might be possible.

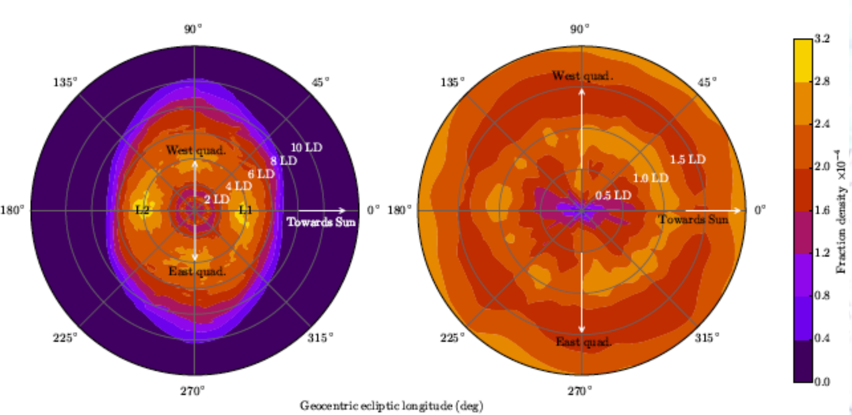
Scaling Analysis: A 12U Cubesat would be roughly 1/6 the mass of an ALSEP-like (100 kg versus 15 kg) and, for two to three instruments, require about 1/6 the mass of batteries to support <1/6 of the power requirement (65 W versus <10 W). 2 Cubesat battery packs (2@ 20Ah) should be good for 20W/hour for 2 hours (5W for 8 hours) and require ¾ U volume. A 10% duty cycle over 14 days (32 hours) running at 5W/hour would require 4 times the battery volume (3U). A system requiring 10W/hour could run at a 5% duty cycle. Assuming a passive thermal design, this power level could allow operation of small particle analyzer, electrical field instrument, and UV spectrometer.

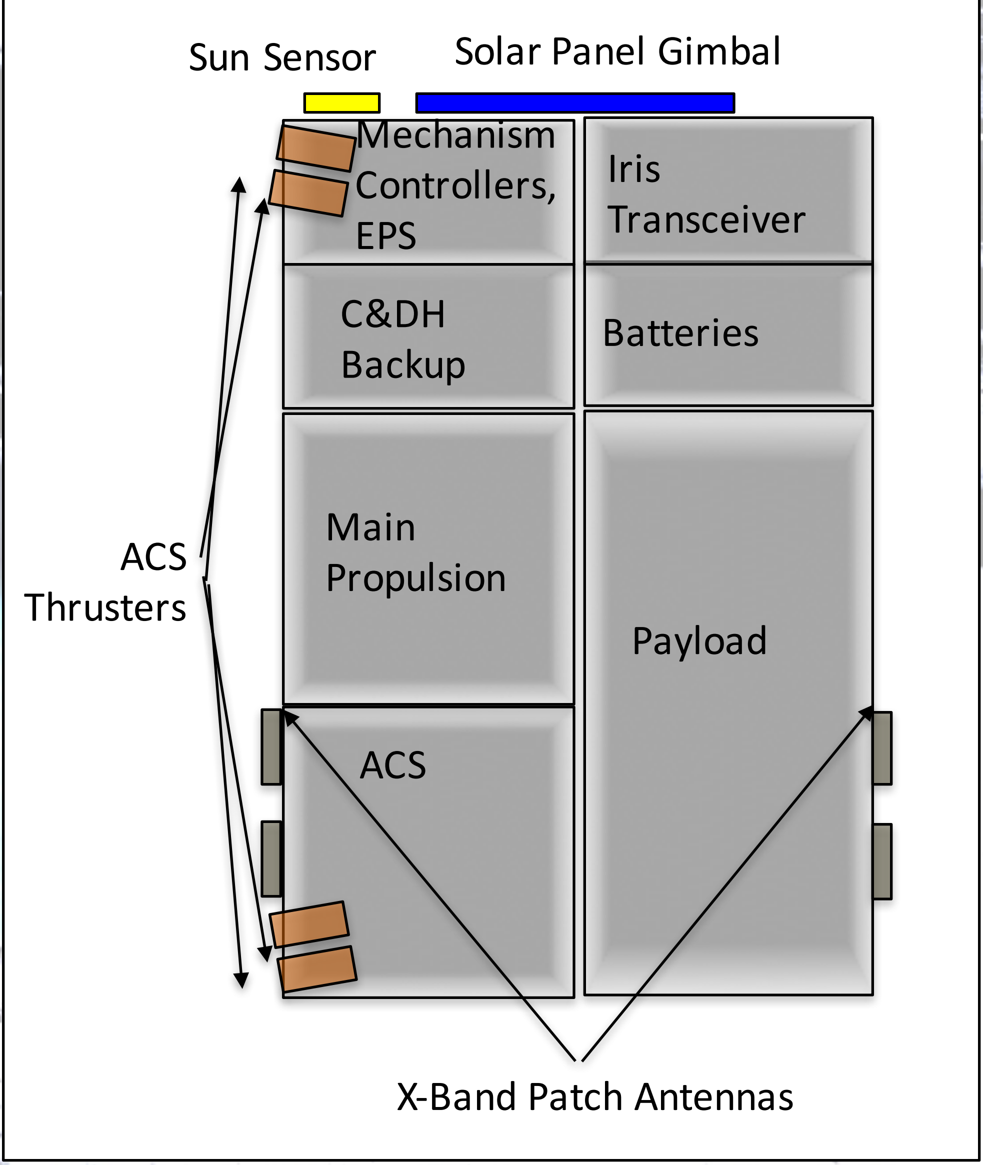
MOLO Concept



How Many Minimoons Are There at Any Time?

- There is always something to visit, but a detailed observational and theoretical study is needed to understand the population!





Sun Sensor

Solar Panel Gimbal

Mechanism Controllers, EPS

Iris Transceiver

C&DH Backup

Batteries

Main Propulsion

Payload

ACS

ACS Thrusters

X-Band Patch Antennas

The Next Frontier: CubeSats for Deep Space

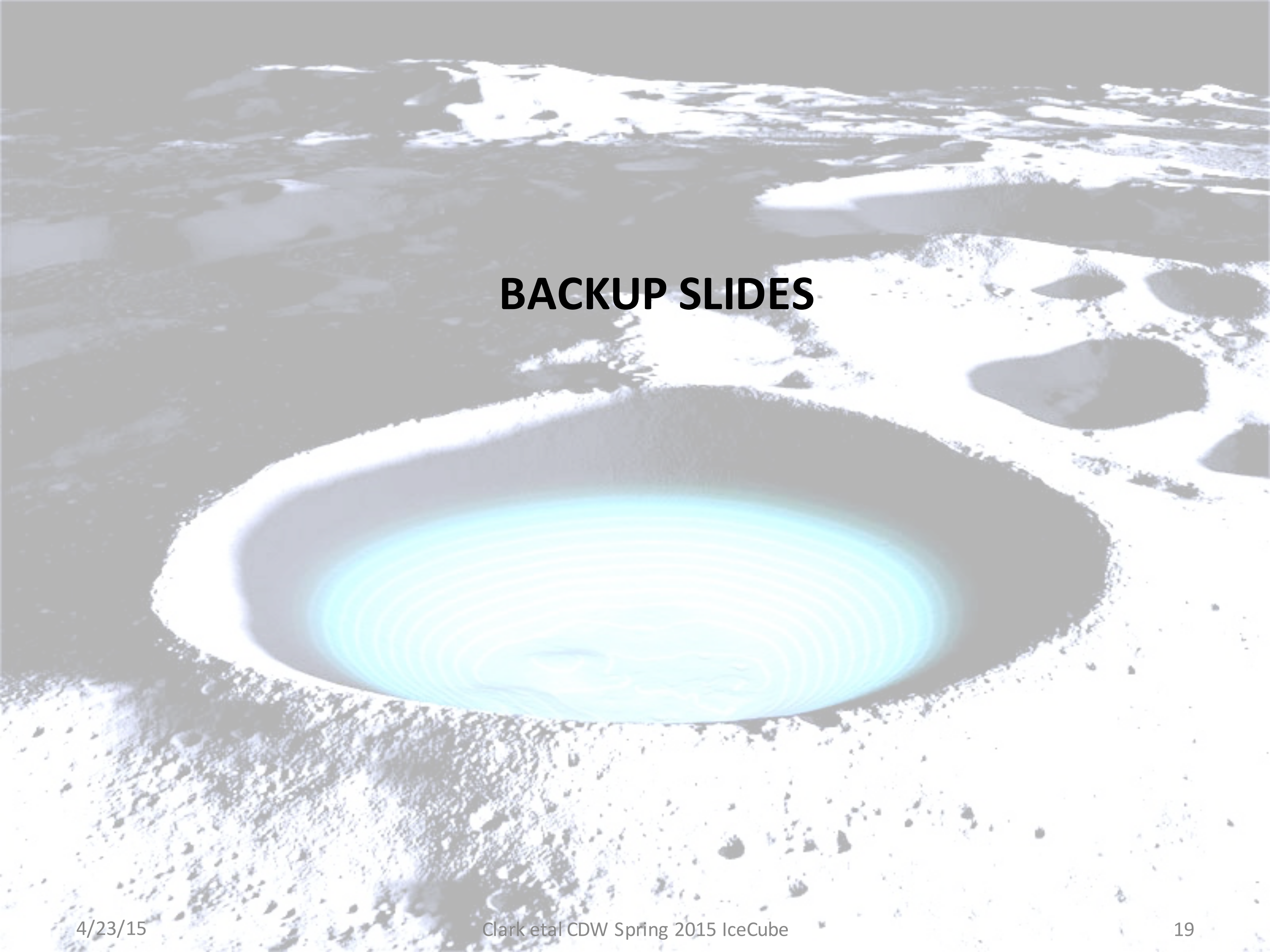
3rd International Workshop on LunarCubes

November 13-15, 2013 – Palo Alto, CA

Lunar Science Illuminating the Universe

1st International Workshop on Scientific Opportunities in Cislunar Space

November 9th, 2014 - Tucson, AZ



BACKUP SLIDES

Every LunarCube Technology Challenges

Thermal/Mechanical, C&DH: Deep space thermal and radiation protection for the thermal (very cold to very hot) with associated mass and volume penalties. Months to years operation instead of days to months for CubeSat.

Solution: New thermally ‘smart’ materials and switches, new multi-layer insulating materials, extra shielding, radiation resistant electronic parts and design. New hybrid batteries with capability for operating at colder temperatures. Radiation hard by design architectures and rad tolerant components.

Communication: communication over far longer distances without supporting infrastructure available for LEO UHF, and with minimal onboard resources (mass, power, volume) for downlink.

Solution: In short run, focused data-taking and minimal navigation and tracking to minimize downlink bandwidth. In long run, use of infrastructure in form of existing landed assets or carrier at target (local DSN) to allow local data transmission and navigation. Use of onboard autonomous optical navigation. Use of laser communication where promising high bandwidth compact systems are being developed, but this requires a laser station infrastructure. Creation of communication network at GEO, and then at progressively further targets.

Every LunarCube Technology Challenges

Power Generation : many 10’s watts power and energy storage during eclipse**.**

Solution: Next generation solar panels to generate up to 100W, special packaging of batteries.

Mobility/Transportation: LunarCube must be delivered beyond LEO as a secondary payload, with the necessity engaging in low energy transfer maneuvers, lunar capture and/changing orbit and will thus require reliable systems capable of efficiently generating kms/sec of delta-V.

Solution: The next generation of compact micropropulsion systems, including MEMS-based electrospray and MicroCathode, are already under development, and are capable of providing more efficient thrust, higher delta V, and higher precision maneuvering and attitude control once at the final destination.

Autonomy: Need for far more internal control, adaptable and stable operation, and ‘smartness’ for proliferating small systems, minimizing need for ground support.

Solution: Frontier Synthetic Neural System enabled Intelligent Decision Engine capable of learning and adapting in response to user demand and environmental changes.

Bus Components

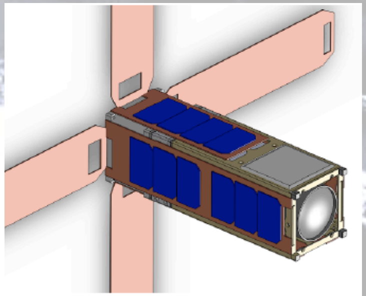
Power:

compactly packaged Li-based batteries (e.g., GOM) that provide adequate power storage for longest 'eclipse' of sun in orbit;

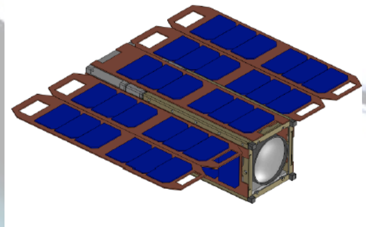
electrical power system, for which many cubesat heritage options are available

Deployable solar panels, for which a number of choices are available (from top to bottom, turkey tail, cross, table, gimballed version of cross). Producers include MMA Design, Honeybee Robotics) Require >50 W running an active propulsion system, which should be more than adequate for other needs when propulsion system isn't running.

trade space cost, mass, reliablity, although volume of solar panels is in the 'cheat space' and doesn't count against 6U total



(a)



(b)